

ELASTIC - PLASTIC FRACTURE MECHANICS OF DUCTILE CAST IRON PIPES

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Abstract

In this paper, depends on the finite element method, the J-Integral program is developed for a stationary circumferential crack problem in elastic – plastic fracture mechanics in pipes under static loading and pure bending moment condition. The program developed is applied to ductile cast iron pipes (DCIP) to analyse the integrity assessment, i.e., the significance of crack growth by drawing both failure assessment diagram (FAD) and crack driving force diagram (CDF). A numerical procedure is used for elastic-plastic analysis depending on special equation to predict J-values taking account of the crack geometry and load condition. It is cleared that the results obtained from failure assessment diagram and crack driving force diagram are identical and J-integral method can be used to the onset of crack growth in (DCIP) under bending moment conditions.

ميكانيكية الانكسار المرنة- اللدنة للأنايبب المصنوعة من حديد الزهر المطبيلي

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الملخص

في هذا البحث، اعتماداً على طريقة العناصر المحددة، تم تطوير برنامج لطريقة تكامل (J) لدراسة وتحليل ميكانيكية الانكسار المرنة-اللدنة لمسائل الشقوق المحيطة في الأنايبب تحت شروط الأحمال السكونية وعزم الانحناء. البرنامج المطور طبق على أنابيب مصنوعة من حديد الزهر المطبيلي لتحليل تقييمها الكامل، أي تحديد بداية نمو الشق والعزم المناظر لبداية نمو الشق من خلال رسم مخطط القوة المسيرة للشق ومخطط تقييم الفشل معاً. تم استخدام طريقة عددية للتحليل المرن – اللدن بالاعتماد على معادلات خاصة لحساب قيمة (J)، اخذين بنظر الاعتبار شكل الشق وشروط التحميل. لقد أظهرت النتائج تطابق القيم المستحصلة من رسم مخطط القوة المسيرة للشق ومخطط تقييم الفشل كما تم إثبات أن طريقة تكامل (J) تكون جداً مفيدة لتحديد بداية ونمو الشق في الأنايبب المصنوعة من حديد الزهر المطبيلي وتحت شروط عزم الانحناء.

Introduction

Cast iron exists in two forms, grey and ductile. In 1955 the ductile cast iron was introduced, when alloying elements were added to make iron less brittle, it was also called nodular cast irons since the shape of the graphite inclusion in the iron is changed to a nodular form. The nodular shape of the graphite inclusions decreases the risk of getting cracks in the material. In general cast iron is the most commonly used material for water main pipes since it is economical to produce and able to withstand the pull stress from the internal pressure [1].

Most ductile cast iron pipes (DCIP) are manufactured in large dimensions because they are less complicated to manufacture and are less expensive.

There are two types of (DCIP) according to uses. Aboveground and underground pipes.

The causes of (DCIP) failures can be classified into two categories as determined from government statistics. These are outside force and corruptions [2]. Homagoun [3] study the combining fuzzy inference and evidential reasoning to quantify the corrosion rate of cast irons and ductile iron pipes. Zencker [4] study the stress intensity factor of dynamically loaded sample of ductile cast iron

containers having crack-like material defects by using numerically calculated method and then verified the result by a comparison with analytical solution.

In this paper, depends on the finite element method, a J-Integral program is developed for a stationary crack under elastic-plastic condition and applied for (DCIP) under bending moment load. Two approaches are used to check integrity assessment, the failure assessment diagram (FAD) and crack driving force (CDF). It is cleared that both approaches are complementary and give identical result.

Fracture Mechanics Procedure

Fracture mechanics problems can be classified into three types according to the dominant operating deformation modes in the cracked bodies [5]:

1- Linear – elastic fracture mechanics (LEFM). In this type the stress-strain behavior and load deformation behavior are linear. The relevant crack tip parameter is the stress intensity factor (K), in this type the plastic zone is small.

2- Elastic-plastic fracture mechanics (EPFM). This type is used for large scale of plasticity and with J-Integral as the relevant crack tip parameters.

3-Time-dependent fracture mechanics (TDFM). This type is used when stress-

starin and load-displacement behavior are time dependent due to either dynamic loading or due to creep.

In ductile material, failure may be governed by growth and fracture which is (J-based) by yeilding and plastic collapse or by an interaction of the two.

Plastic Collapse Load and Plastic Collapse Bending Moment

There are two method of integrity assessment, the first is carried out without postalution of crack and the second is carried out with postalution of cracks. If the piping material is extremely ductile or tough , one need not adopt the fracture mechanics principle at all, elastic – plastic fracture mechanics and limit load concept is sufficient for it's integrity assessment [5]

The plastic collapse load (limit load) and plastic collapse moment (limit moment) of a pipe with circumferential crack under the bending load is given by the following equations [6]:

$$P_1 = \frac{16R^2 t \sigma_f}{Z-L} \left[\cos\left(\frac{\theta}{2}\right) - 0.5 \sin(\theta) \right] \quad \dots(1)$$

$$M = 4R^2 t \sigma_f \left[\cos\left(\frac{\theta}{2}\right) - 0.5 \sin(\theta) \right] \quad \dots(2)$$

where,

R: outer pipe radius

t: pipe walll thickness.

$$\sigma_f = \frac{\sigma_y + \sigma_u}{2}$$

σ_y : yeild strangth.

σ_u : tensile strangth.

Z: outer span.

L: inner span.

θ : half crack angle.

J-Integral Approaches

Under elastic-plastic condition and deformation theory of plasticity, the crack driving force, J , can be obtained by adding the elastic component, J_e , and plastic component , J_p , [5] i.e.

$$J = J_e + J_p \quad \dots(3)$$

For a circumferential crack pipe under bending , closed form expression can be developed for both J_e and J_p . They are discussed as follows:

A-Plastic solutions

The plastic component , J_p can be found by using two approaches:

1- The plastic compoenent J_p can be defined as [7]:

$$J_p = \int_0^M \frac{\partial \phi_p}{\partial A} dm = \frac{\partial}{\partial A} \int_0^M \phi_p dm \quad \dots(4)$$

where,

$$\varphi_p = \left(\frac{t}{t_e}\right)^{n-1} \left(\frac{\pi}{4\hat{K}}\right)^n \left(\frac{m}{m_o}\right)^{n-1} \\ * \left(\frac{2m}{\pi R_M^4 t^2 E}\right) I\left(\frac{\theta}{\pi}\right) * \alpha$$

$$\hat{K} = \frac{\sqrt{\pi}}{2} \frac{\Gamma\left(1 + \frac{1}{2n}\right)}{\Gamma\left(\frac{3}{2} + \frac{1}{2n}\right)}$$

$$I\left(\frac{\theta}{\pi}\right) = (2\theta) \left[\left(R_M - \frac{t}{2}\right) \int a F_B^2\left(\frac{\theta}{\pi}\right) da \right. \\ \left. + \int a^2 F_B^2\left(\frac{\theta}{\pi}\right) da \right]$$

$$F_B\left(\frac{\theta}{\pi}\right) = 1.1 + [-0.09967 \\ + 5.0057\left(\frac{\theta}{\pi}\right)^{0.565} - 2.8329\left(\frac{\theta}{\pi}\right)]$$

and,

$$m_o = \pi R_m^2 t \sigma_o \text{ (reference moment).}$$

R_m : mean radius of pipe.

t_e : equivalent thickness of uncrack .

α : model parameter.

n : strain hardening exponent.

σ_o : reference stress .

a : distance of crack from inner radius.

2- The plastic component can also be determine by using the following equation [8]:

$$J_p = J_{p_o} + \int_{\theta_o}^{\theta} \gamma J_{p_o} d\theta \quad \dots (5)$$

where,

$$\gamma = \frac{[0.5 \cos(0.5\theta) - \sin\theta]}{\sin(0.5\theta) + \cos\theta}$$

$$J_{p_o} = \int_0^{\Delta P_i} \eta_{p_i} d(\Delta P_i)$$

$$\eta_{p_i} = \frac{0.5 [\sin(0.5\theta) + \cos\theta]}{2Rt [\cos(0.5\theta) - 0.5 \sin\theta]}$$

$$\Delta P_i = \alpha \varepsilon_o a b (W_r, n) \left[\frac{f}{f_y} \right]^n$$

$$\varepsilon_o = \frac{\sigma_o}{E}$$

and,

θ : semi-circumferential crack angle.

P : total applied load (plastic load).

α : dimensions parameter.

F and F_y : applied and limit load .

ΔP_i : load – line displacement

$b(W_r, n)$: factor depending on strain hardening (n) and crack to width ratio (W_r)

The functions $I\left(\frac{\theta}{\pi}\right)$ and J_{p_o} can be

computed by using the finite element method. The program is developed by using four – noded shell element with three displacement and two rotational degree of freedom at each node. Then J_p can be culculated using eq.4 and eq.5.

B- Elastic solution

The value of J-Integral in elastic portion for a pipe having circumferential crack for plain strain conditions is given by [6]:

$$J_e = \frac{1-\nu^2}{E} K_I^2 \quad \dots (6)$$

The stress intensity factor (K_I) for a pipe subjected to bending moment is :

$$K_I = \sigma_b \sqrt{\pi R \theta F_b}$$

where,

$$\sigma_b = \frac{M}{\pi R^2 t}$$

$$F_b = 1 + A \left[4.5967 \left(\frac{\theta}{\pi} \right)^{1.5} + 2.6422 \left(\frac{\theta}{\pi} \right)^{4.24} \right]$$

$$A = \left(0.4 \frac{R}{t} - 3.0 \right)^{0.25} \quad \text{for } \frac{R}{t} \geq 10$$

and,

M: bending moment.

ν : poisson's ratio.

E: Young modulus.

Ductile Iron Pipe Dimensions and Properties

Ductile iron pipe is normally manufactured in (216"- 240"), nominal length depends on the pipe manufactured and pipe size Fig.1 [9]. Fig.2 show DCIP and finite element mesh for the following dimensions (r_i

= 12.08" (318.356 mm); r_o =12.4" (327.5 mm); and t = 0.36" (9.144 mm)), and having the following elastic properties [10]:

$$E = 169 \text{ GN/m}^2; \quad \rho = 7100 \text{ kg/m}^3$$

$$\sigma_y = 276 \text{ MN/m}^2; \quad \nu = 0.29$$

$$\sigma_u = 414 \text{ MN/m}^2;$$

Also for DCIP material the following values of constant are given [7]:

$$\alpha = 1, \quad n = 0.106, \quad t_c = 0.5 t$$



Fig.1 Ductile iron pipe on support

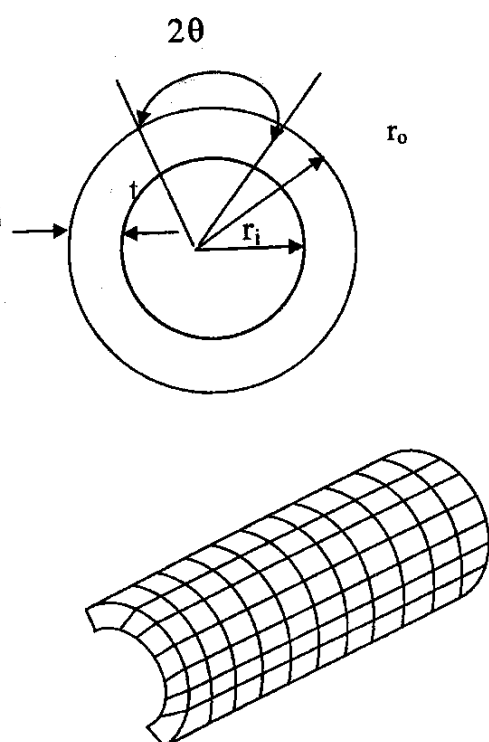


Fig.2 Details of iron pipe and finite element mesh for half pipe.

If the material properties are taken as above, the fracture toughness (K_{IC}) in specific design are depending in extensive investigation of ferritic in ductile iron over a board range of microstructure and temperature [10]. Elsewhere, used $K_{IC} \geq 50 \text{ MPa} \cdot \sqrt{\text{m}}$ [4].

Result and Discussions

Fig.3, show J- values for plastic portion goted from Eq.4 and Eq.5. As shown there is a very good agreement between these values.

Fig.4 show failure assessment diagram (FAD) and loading curve. The

(FAD) getting from drawing the values of (K_r) i.e., the stress intensity factor divided by fracture toughness of material and (L_r) i.e., applied load divided by limit load. From this figure it can be seen two regions: stable region (safe) which defined as the conditions of crack growth during which the applied value of (K) for linear elastic conditions equal the resistance of material to fracture, and unstable region (unsafe), this shown fracture condition to propagate untile complete fracture occurs.

The point where intersects between failure assessment diagram and loading curve give the value of (L_r) for crack initiation and from this crack initiation moment can be calculated. In Fig.4 $L_r = 0.39$ and the crack initiation moment = 471 kN.m

To check this value of crack initiation moment we plote the initiation value of (J_i) and applied J- value against applied moment in Fig.5, and the point of intersection of J- values and J_i - line give applied moment 1.2 MN.m and the crack initiation moment is equal to $(1.2 \cdot 10^3) \cdot 0.39 = 468 \text{ kN.m}$.

To obtain failure bending moment, the J-values calculated for elastic -

plastic using given procedure and for increasing values of applied moment (by take any some of values of applied moment above crack initiation moment) are plotted against varies values of crack size as shown in Fig.6. The J-material curve (J-values calculated from K_m) is also plotted in the same figure. The point where the slope of J-against half crack angle and J-material curve are the same will give failure moment. Failure bending moment = 503 kN.m.

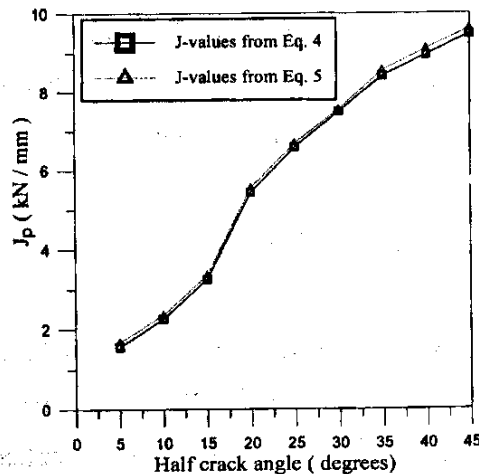


Fig.3 J- values for plastic a portion vs. crack angle

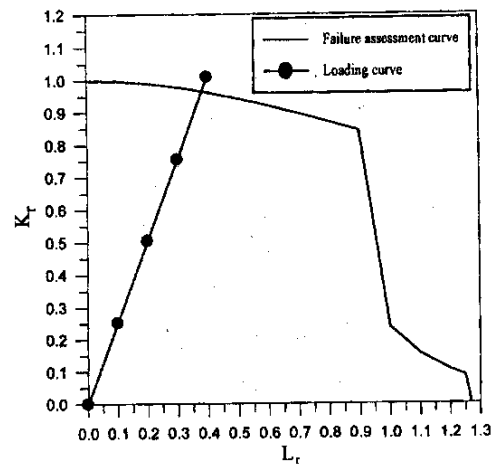


Fig.4 Failure assessment diagram

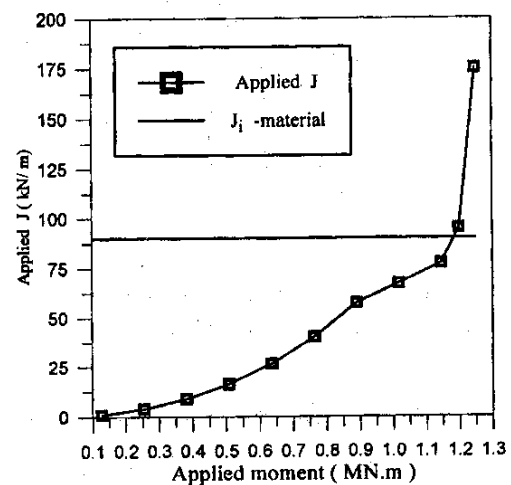


Fig.5 J- values against applied moments

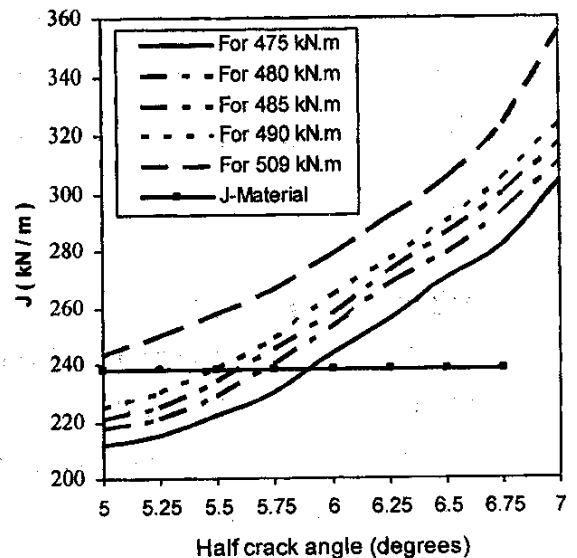


Fig.6 J against crack extension curve

Conclusions

The J-integral has been analysed for circumferential crack and we may claim that J-integral will be a useful method to evaluate the onset of crack growth under bending moment loading. From discussion before we can conclude the following remarks:

- 1-For plastic problems, J-Integral result presented good agreement between numerical procedure used for analysis.
- 2- An increase in the crack angle will increase the J-values result from increasing stresses in the crack tip.
- 3- For DCIP, there will be significant unstable crack growth before final fracture.

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