ELASTIC - PLASTIC FRACTUR 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 analys 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 الأنكسار المرنة_اللدنة للأنابيب المصنوعة من حديد الزهر المطيلي

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الملخص

في هذا البحث، اعتمادا على طريقة العناصر المحددة، تم تطوير برنامج لطريقة تكامل (J) لدراسة وتحليل ميكانيكية الانكسار المرنة–اللدنة لمسائل الشقوق المحيطية في الأنابيب تحت شروط الأحمال السكونية وعزم الانحناء. البرنامج المطور طبق على انابيب مصنوعة من حديد الزهر المطيلي لتحليل تقيمها الكامل، اي تحديد بداية نمو الشق والعزم المناظر لبداية نمو الشق من خلال رسم مخطط القوة المسيرة للشق ومخطط تقييم الفشل معا. تم استخدام طريقة عددية للتحليل المرن – اللدن بالاعتماد على معادلات خاصة لحساب قيمة (J) ، اخذين بنظر الاعتبار شكل الشق وشروط التحميل. لقد اظهرت النتائج تطابق القيم المستحصلة من رسم مخطط القوة المسيرة للشق ومخطط تقييم الفشل كما تم إثبات ان طريقة تكامل (J) تكون جدا مفيدة لتحديد بداية ونمو الشق في الأنابيب المصنوعة من حديد الزهر المطيلي وتحت شروط عزم الانحناء.

Introduction

Cast iron existes in two forms, grey and ductile. In 1955 the ductie cast iron was introduced, when alloying element 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 crackes 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 irons pipes (DCIP) are manufactured in large dimensions because they are less complicated to manfacture 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 corrosions [2]. Homagoun [3] study the combining fuzzy infloreena and evidential reasoning to quantify the corrosion rate of cast irons and ductile irons pipes. Zencker [4] study the stress intesity 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 comparision 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 complemetary and give identical result.

Fracture Mechanics Procedure

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

1- Linear – elastic fractuer mechanics (LEFM). In this type the stress-strain behavior and load deformation behavior are linaer . 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 stressstarin 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]:

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

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

where,

R: outer pipe radius

t: pipe walll thickness.

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

σ_y: yeild strength.

σ_u: tensile strength.

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.

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

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]:

$$J_P = \int_0^M \frac{\partial \varphi_p}{\partial A} dm = \frac{\partial}{\partial A} \int_0^M \varphi_p dm \quad ...(4)$$

where,

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

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

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

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

and,

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

R_m : mean radius of pipe.

t_e : equivalent thickness of uncrack .

α : model parameter.

n: strain hardining 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]:

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

where,

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

$$J_{\rho_o} = \int_0^{\Delta P_i} \eta_{P_i}\,d(\Delta P_i)$$

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

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

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

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 hardining (n) and crack to width ratio (W_r)

The functions $I(\frac{\theta}{\pi})$ and J_{ρ_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: poissoin'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]:

$E = 169 GN/m^2$; $\rho = 7100 kg/m^3$

$\sigma_y = 276 MN/m^2$; $\nu = 0.29$

$\sigma_u = 414 MN/m^2$;

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

$\alpha = 1$, $n = 0.106$, $t_e = 0.5\,t$

Fig.1 Ductile iron pipe on support

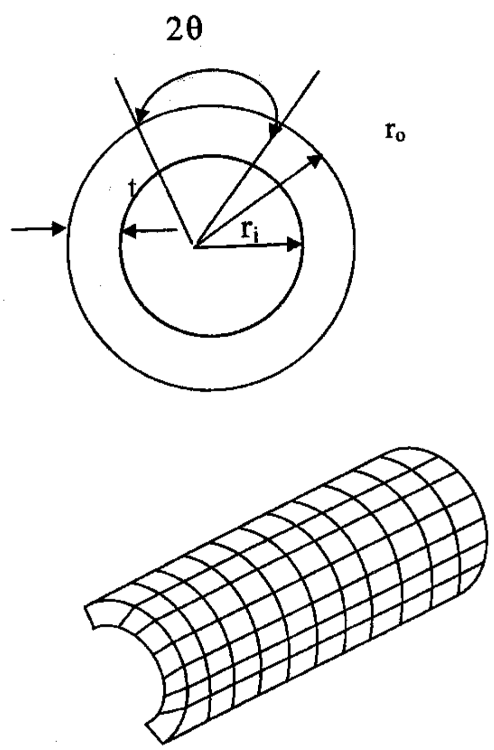

Fig.2 Details of iron pipe and finite element mesh for half pipe.

If the material properties are taken as above, the fracture toughness (K_{IC}) in speciefic design are depending in extensive investigation of ferritic in ductile iron over a board range of microstructure and temperature [10]. Elsewhere, used $K_{IC} \geq 50 MPa.\sqrt{m}$ [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 drawning 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 condtion 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 intiation and from this crack intiation moment can be calculated. In Fig.4 L_r = 0.39 and the crack intiation moment = 471 kN.m

To check this value of crack intiation moment we plote the intiation 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 $(1.2*10^3) * 0.39 = 468$ 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 intiation moment) are plotted against varies values of crack size as shown in Fig.6. The J-material curve (J-values culculated 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.

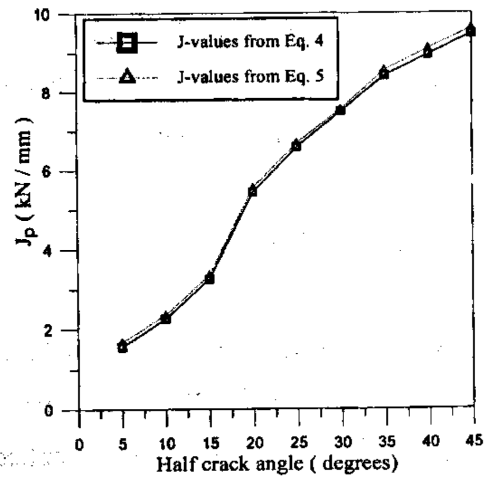

Fig.3 J- values for plastic a portion vs. crack angle

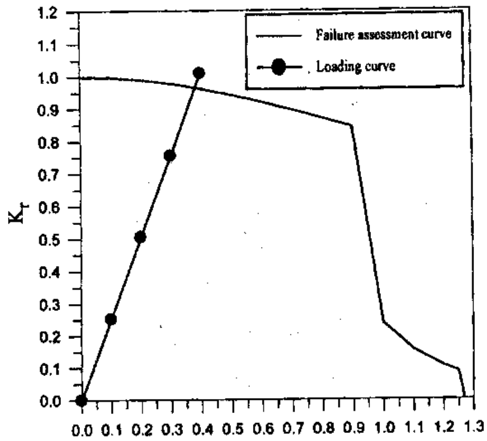

Fig.4 Failure assessment diagram

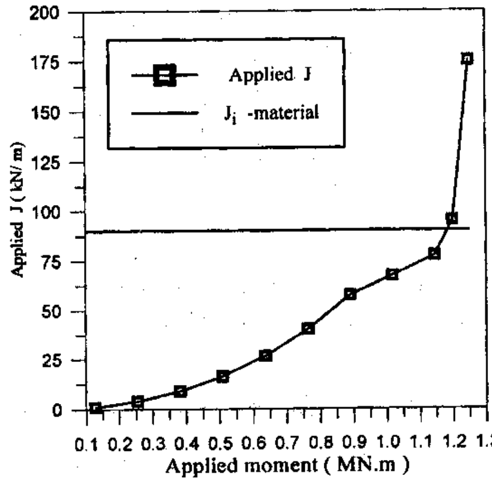

Fig.5 J- values against applied moments

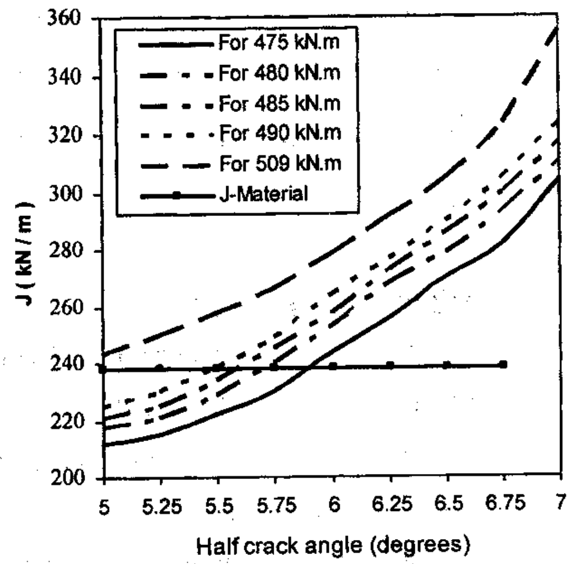

Fig.6 J against crack extension curve

Conclusions

The J-integral has been analysed for circumferential crack and we may claim that J-integral will be a useful method to evalute the onset of crcak 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 increas in the crack angle will increas the J-values result from increasing stresses in the crack tip.

3- For DCIP , there will be sigificant unstable crack growth before final fracture.

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