A STUDY ON FAILURE STRESS AND FATIGUE CRACK RATE IMPLEMENTED TO A DOUBLE EDGE NOTCHED GUSSET PLATE (AN ANALYTICAL INVESTIGATION BASED ON FRACTURE MECHANICS)

by Agnes Hanna Patty

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A Study on Failure Stress and Fatigue Crack Rate Implemented to a Double Edge Notched Gusset Plate

(*an Analytical Investigation Based on Fracture Mechanics*)

Agnes H. Patty*
Widya Karya Catholic University Malang, Email: agneshpatty@widyakarya.ac.id
Benedictus Sonny Yoedono
Widya Karya Catholic University Malang, Email: sonny_ft@widyakarya.ac.id
Danang Murdiyanto
Widya Karya Catholic University Malang, Email: danang_t.mesin@widyakarya.ac.id
Andy Rahmadi Herlambang
Jakarta Global University, Email: andyherlambang@jgu.c.id

Abstract

A gusset plate is a member of a bridge structure that is significantly subjected to cyclically varying loads. It may collapse after a certain number of cycles. However a single cycle may causes structural failure although the maximum stress (due to loading) is much less than the yield or the ultimate stress of the material. In a case of notched component under such conditions, high-intensity stress will occur at the zone of the notched component. Fracture mechanics is strongly recommended in a bridge design especially for joints. It will determine the moment at which fatigue cracks will occur and how far it has propagated. This study explores a fracture phenomenon of a steel gusset plate due to fatigue loading. Modeled as a double-edged notched plate, the failure stress is found to be less than the ultimate stress of the material. By assuming that crack closure exist, the results of this study provide a significant conclusion: under a constant failure stress the rate of fatigue growth increases as the crack propagates.

Keywords: Fracture mechanics, fatigue loading, stress intensity, double-edge notched

Abstrak

Pelat buhul adalah bagian dari struktur jembatan yang secara signifikan mengalami beban yang bervariasi secara berulang. Pelat buhul dapat runtuh setelah sejumlah siklus tertentu. Namun satu siklus dapat menyebabkan kegagalan struktur meskipun tegangan maksimum (akibat pembebanan) jauh lebih kecil daripada tegangan leleh atau tegangan ultimit material. Pada kasus komponen bertakik dalam kondisi seperti diatas, tegangan dengan intensitas tinggi akan terjadi pada zona komponen bertakik. Mekanika fraktur sangat direkomendasikan dalam desain jembatan terutama untuk sambungan. Mekanika fraktur akan menentukan saat dimana retak lelah akan terjadi dan seberapa jauh perambatannya. Penelitian ini membahas fenomena fraktur pada pelat buhul baja akibat beban lelah. Dimodelkan sebagai pelat bertakik bermata dua, tegangan runtuh ditemukan lebih kecil dari tegangan ultimate material. Dengan mengasumsikan adanya penutupan retak, hasil penelitian ini memberikan kesimpulan yang signifikan: di bawah tegangan runtuh yang konstan, laju pertumbuhan lelah meningkat seiring dengan perambatan retak.

Kata-kata Kunci: *Mekanika fraktur, pembebanan kelelahan, intensitas tegangan, berlekuk dua sisi*

1. Introduction

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Fracture mechanics is the study of the response and failure of structures as a consequence of crack initiation and propagation (Shah, at. al., 1995) (Broek, 1986). Dealing with failure of bridge structures, assumption in this case were made to be linear rapid failure where LEFM should be applied. By considering the failure phenomenon shown in **Figure 1,** one may question what parameters are critical.

Loading capacity of structures may be based on strength state when strength criterion is used for designing or, toughness (stress intensity factor K or fracture energy (G) when fracture mechanics is used as failure criterion. Following are the formulas to be met in strength state criterion.

$$N_n = A_e f_u \quad (1)$$

for effective cross section

$$N_n = A_g f_y \quad (2)$$

for gross cross section.

* *Penulis Korespondensi: agneshpatty@widyakarya.ac.id*

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Figure 1. Failure of steel truss bridge

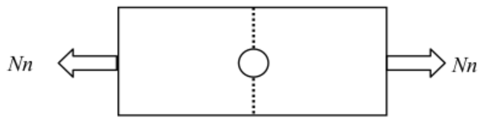

Figure 2. Plate under tension

An understanding of the concept of fracture mechanics, namely, in relation to structural failure, is important to anticipate the sudden collapsing. Hence, parameters such as crack size and geometry, residual strength, crack rate propagation, etc., need to be significantly ascertained. The main goal is to schedule rehabilitation on structural elements that are notched sensitive.

To determine the capacity of such case shown in **Figure 2** based on the perspective of fracture mechanics, the following requirement must be taken into accounts:

$$K = f(g)\sigma\sqrt{\pi a} < K_c \qquad 3$$

where

σ = stress applied to the component
A = crack length
$f(g)$ = geometry factor
K_c = the critical of stress intensity factor

For infinitely wide plate, failure stress can be written as

$$\sigma_f = \frac{K_c}{f(g)\sqrt{\pi a}} \qquad 4$$

Where $f(g) = 1$

The permissible length which is expected for an inspection schedule can be written as (ASTM E647) (Bannantine, 1990).

$$a_{cr} = \frac{1}{\pi}\left[\frac{K_C}{f(g)\sigma}\right]^2 \qquad 5$$

Please note, beyond K_c the crack propagates rapidly. K_c is material toughness which can be also defined as $\sqrt{EG_c}$, where E is modulus of elasticity, and G_c is fracture energy.

2. Problem of Fatigue

Bridge is significantly subjected to dynamic loading where the effect of fatigue phenomenon has to be accounted in the analysis particularly for joints. In case of gusset plates, one need to measure the range of the stress intensity factor $\Delta K=K_{max}-K_{min}$, hence, the critical length (a_{cr}) in eq.5 can be re-written as

$$a_{cr} = \frac{1}{\pi}\left[\frac{K_C}{f(g)\Delta\sigma}\right]^2 \qquad 6$$

The correction factor $f(g)$ is calculated based in the following (Ewalds and Wanhill, 1984).

$$f(g) = \frac{1.122 - 0.561\left(\frac{a}{w}\right) - 0.205\left(\frac{a}{w}\right)^2 + 0.471\left(\frac{a}{w}\right)^3 - 0.190\left(\frac{a}{w}\right)^4}{\sqrt{1-\frac{a}{w}}}$$

K_{max} and K_{min} are corresponding with σ_{max} and σ_{min} respectively. σ_{max} - σ_{min} is the stress range shown in **Figure 3**.

It is well known that stress intensity factor (K) is most depends on crack-tip geometry. The sharper the crack-tip the higher the value of K. If K exceeds its critical value then it is less likely for crack closure to occur as a result of crack-tip plasticity. Then the consequence is rapid failure.

In the early 1970's, Elber observed that the surfaces of the fatigue cracks close (*contact each other*) when the remotely applied load is still tensile and do not open again until a sufficiently high tensile load is obtained on the next loading cycle (Elber, 1971).This implies that in case of fatigue loading with R>0, prevails to such a crack retardation due to crack closure.

A basic formula to express the crack growth rate is (Paris and Erdogan, 1963)

$$\frac{da}{dN} = (C\Delta K_{eff})^m \qquad 8$$

and cycles to failure N_f may be written as

$$N_f = \int_{a_i}^{a_f} \frac{da}{C(\Delta K_{eff})^m} \qquad 9$$

Where $\Delta K_{eff} = U\Delta K$ 10

U may be taken as $0.5+0.4R$ which is valid only when $R > 0$.

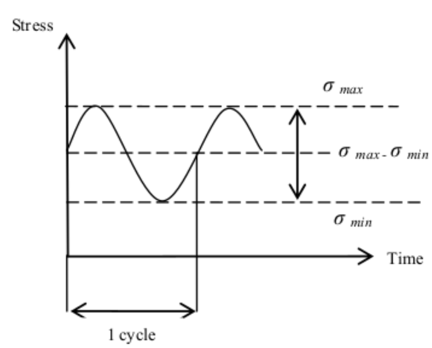

Figure 3. Stress range

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3. Case Study

Consider a gusset plate made from steel containing notched cracks as shown in **Figure 4a**, and modeled as a double edge shown in **Figure 4b**. The gusset plate is subjeted to $R>0$, with stress range $\Delta\sigma$ = 300 MPa. Supposing that crack closure existed, and material constant to be m = 3 (Throop and Miller, 1970), find the fatigue crack growth rate for each crack extension da = 1 mm

Followings are the material properties (Roylance, 1996) and the solution

Kc = 1565.33 MPa√mm
Fy = 590 MPa
Fu = 1200 Mpa

1. Determine C or $f(g)$ as a corection factor; from eq. 7, C = 1.130
2. Final critical crack length

$$a_f = \frac{1}{\pi}\left[\frac{K_C}{f(g)\Delta\sigma}\right]^2$$

$$a_f = \frac{1}{\pi}\left[\frac{1565.33}{300(1.130)}\right]^2$$

$a_f = 6.8\ mm$

3. Failure stress due to the critical stress intensity factor

$$\sigma_f = \frac{Kc}{f(g)\sqrt{\pi a}} \rightarrow C = f(g) = \text{geometry factor}$$

$$\sigma_f = \frac{1565.33}{1.130\sqrt{\pi(117)}}$$

$a_f = 72.27\ MPa$

4. Stress intensity range for the first 1 mm crack extension

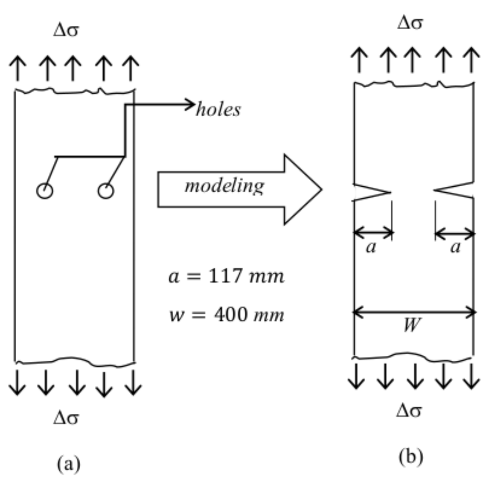

Figure 4. Gusset plate under cyclically loading (a) Actual (b) Model

$$\Delta K = C\Delta\sigma\sqrt{\pi a_f}$$

$$\Delta K = 1.130\ x\ 300\sqrt{\pi(118)}$$

$$\Delta K = 6527.349\ \text{MPa}\sqrt{\text{mm}}$$

5. Efective stress intensity range for the first crack extension da = 1 mm

U = 0.5 + 0.4R
U = 0.5 + 0.4(0.3)
U = 0.62

$$\Delta K_{eff} = U\Delta K$$

$$K_{eff} = U\ (C\Delta\sigma\sqrt{\pi a_f})$$

The same procedure can be made for each crack extention da = 1 mm, to find the fatigue crack growth rate.

6. Failure stress due to ΔK_{eff} each time da = 1 mm is reached by calculating

$$\sigma_f = \frac{\Delta K_{eff}}{C\sqrt{\pi a_f}}$$

$$a_f = a_i + 1$$

7. Futhermore, fatigue crack growth rates are calculated using

$$\frac{da}{dN} = C[\Delta K_{eff}]^m$$

where m = 3 (Throop and Miller, 1970)

4. Disscusion

1. The failure stress σ_f= 186.056 MPa (corresponding with ΔK_{eff}) is found lower than yield stress of the material (fy = 590 MPa). It means that due to fatigue loading structures could be failed not because of the exceeded of the static strength (yield or ultimate), but because of the exceeded of the critical stress intensity factor (K_C = 1565.33 MPa √mm).
2. The final crack (a_f = 6.8 mm) represents the critical length. It is imperative for an inspection to be scheduled before the crack propagation reaches that value, otherwise, structure failure is unavoidable and more rapidly in a case of brittle materials.
3. The application of fracture mechanics is very useful for lap joint such as this case for both, slip and non-slip connection.
4. Shown also that the rate of the fatigue crack growth faster as the crack propagates.

5. Conclusion

1. Fracture mechanics offers all aspects regarding structural failure. The basis of LEFM, is that energy absorbed during loading will be released rapidly to create crack and separate it as well.

2. This is valid for a brittle fracture with a very small plastic zone at the crack tip. Steel is a ductile

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Table 1. Fatigue crack propagation rate

w (mm)	Δσ (MPa)	a_i (mm)	a_f(mm)	f(g)=C	$\Delta K = C\Delta\sigma\sqrt{\pi a_f}$ (MPa√mm)	ΔK_{eff}	Cycles to extend 1mm $N_f = \int_{a_i}^{a_f} \frac{da}{C(\Delta K)^m}$ (cycles/mm)
400	300	117	118	1.130	6527.349	4046.96	1.33476E-11
400	300	118	119	1.131	6556.568	4065.07	1.31667E-11
400	300	119	120	1.131	6585.720	4083.15	1.29894E-11
400	300	120	121	1.131	6614.809	4101.18	1.28155E-11
400	300	121	122	1.131	6643.837	4119.18	1.26449E-11
400	300	122	123	1.132	6672.806	4137.14	1.24776E-11
400	300	123	123.8	1.132	6696.311	4151.71	1.23432E-11

material; LEFM is still applicable if one uses ΔK_{eff} instead of ΔK as a consequence of crack closure.

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