Fracture Analysis of CT Specimens of Low Strength Alloy Steels

M. T. AYOUB,
Alexandria University, Alexandria, Egypt

ABSTRACT

The compact tension test is conducted herein for different low strength alloy steel yield strength ranging from 40 to 80 Ksi and a load displacement record is provided for each. Relative displacement of CT specimen apart is measured analogus to the concept of critical crack extension forçe to relate displacement to plane strain fracture toughness K_c. Moreover a math model for the CTS results is derived to rélate the crack opening displacement to the applied force and rack length wether there is a considerable plastic flow ahead of the crack or not.

The calculated fracture toughness characterizing the resistance of the material during incremental crack extension is compared with that obtained experimentally. The agreament of the toughness results wether in the elasto-plastic or plastic regions indicate the possibility of using CTS results in the nonlinear analysis. Therefore an evaluation of R-curves will be provided directly for low strength, high toughness alloy steels.

INTRODUCTION

Almost all low to medium strength alloy steels that are used in section sizes for large structures are of insufficient thickness to maintain plane strain conditions under service loading. Moreover low alloy steel with high toughness quality always performing large scale crack-tip plasticity which invalidate the linear elastic analysis as a finder for the fracture toughness. Accordingly, the plane stress critical intensity factor K_c will represent the true fracture toughness for such types of materials. Furthermore, working conditions and thickness of most structural materials used in practice are generally such that plane-stress rather than plane-strain conditions actually exist in service. The R curve method or the crack growth resistance plot is used in this paper to emphazie the effect of crack extension a at a particular instability condition. A math model is provided to prescribe the

the critical stress intensity K_c to the energy required to produce unit change in the crack area R. Compact tension specimen, fig.(1) are tested for plotting the slow applied loading versus the crack-opening displacement to be used in calculating the critical stress intensity K_c. This nonlinear approach is based on theoretical considerations of energy balance. The application of c.o.s. method to R curve testing has been developed by McCabe and Heyer(1) for any type of test procedure like CTS which have been used in this study. And since the testing procedure for R curve evaluation are rather complex and still not standardised, the R curves provided in this study are theoretically evaluated and compares with the available experimental one particularly for the A 572 Grade 50 steel on hand.

MATH MODEL FINDER OF FRACTURE TOUGHNESS

For toughness measurements in the elastic-plastic regions by using CTS, the importance of specimen design becomes essential. However the derived math model regardless of the specimen dimension will prescribe the change of specimen stiffness with respect to its crack area as described in (2). The energy balance is written in differential form as follows:

$$Pdu = d(\tfrac{1}{2}pu) + R\,da \qquad (1)$$

which upon expanding, rearranging and dividing by u^2 gives,

$$\frac{pdu}{u^2} - \frac{dp}{u} = \frac{2R}{u^2}\,da$$

or

$$-d\left(\frac{p}{u}\right) = \frac{2R}{u^2}\,da \qquad (2)$$

thus

$$u^2 = \frac{-2R}{\frac{d}{d}\left(\frac{P}{u}\right)} \qquad (3)$$

The stiffness p/u is obtained for split specimen as a beam strip as shown in fig(2), the strain energy of bending a splitted CTS may be written as (considering $\acute{u}$ for each split)

$$\tfrac{1}{2}\,p\acute{u} = \tfrac{1}{2}\int \frac{M^2}{EI}\,dl \qquad (4)$$

$$\acute{u} = \frac{p^2}{3EI}\,[a + r\,(w-a)]^3$$

put $u = 2\acute{u}$ and divide by p^2

$$\therefore \frac{u}{p} = \frac{2\,[a+r(w-a)]^3}{3EI} = \frac{2\,A^3}{3EIt^3} \qquad (5)$$

where $A = [a + r\,(w-a)]\,t = f\,a\,t$

f = factor

and r is a factor varies from 1/3 to 1/4(for most of alloy steels experimental data reveal a value for r=1/3 as in (1)). Therefore,

$$\frac{p}{u} = \frac{3EIt^3}{2A^3}$$

thus

$$\frac{d}{dA}\left(\frac{p}{u}\right) = \frac{-9EIt^3}{2A^4} \qquad (6)$$

substituting into equation(6) from equation (2) gives,

$$u^2 = \frac{-4RA^4}{-9EIt^3}$$

$$= \frac{4A^3}{9It^3}\;\frac{R}{E}\;A \qquad (7)$$

Accordingly, for a particular specimen geometry and starting crack area ΔA, a measure of R will lead directly to the fracture toughness K_c if a plane stress condition is satisfied, so if $R = K_c^2/E$ equation (7) will be

$$u = \sqrt{\frac{4\,f^3a^3}{9I}}\;\frac{K_c}{E}\;\sqrt{A} \qquad (8)$$

Substituting for A from the general expression that

$$K_c = C\,\sigma\,A^{\frac{1}{4}} \qquad (9)$$

Therefore equation (8) becomes

$$u = \sqrt{\frac{4\,f^3a^3}{9I}}\;\frac{K_c^2}{EC\,\sigma} \qquad (10)$$

The equivalent expression for δ_c instead of u will be,

$$\delta_c = \frac{[r(w-a)]}{[a + r(w-a)]}\;u \qquad (11)$$

$$= n\,u$$

Therefore, the crack opening displacement δ_c is obtained,

$$\delta_c = n\sqrt{\frac{4f^3a^3}{9I}}\;\frac{K^2}{EC\,\sigma}$$

The stress σ which causing the formation of a plastic hinge leading the crack tip will reach to the yield stress, putting $\sigma = \sigma_y$ and $E = \sigma_y/\epsilon_y$

Therefore

$$\delta_c = \frac{N}{C}\,\frac{(K_c)^2\,\epsilon_y}{\sigma_y} \qquad (12)$$

where,

$$N = n\,\frac{4f^3a^3}{9I}$$

$$C = \sqrt{\frac{\pi}{t}}$$

for the CTS with a = t = w/2 =1.5 inch, H = 0.6 w and r=1/3, therefore the constants in equation (12)

$$n = 1/4\ ,\ f = 4/3\ ,\ C = 1.447$$

$$I = \frac{tH^3}{12} = (1.2a)^3\ t/12 = 0.144\ a^3t$$

$$N = 1/4\ \frac{4(4/3)^3}{9(0.144)(1.5)}$$

$$= 1/4\ \frac{9.481}{1.944} = 0.552$$

$$N/C = \frac{0.552}{1.447} = 0.381$$

It may be worthy to mention herein that Egan(3) has extrapolated an experimental values for N/C = 1.0, 2.0 for elastic and elastio-plastic behaviour of K_{ic} respectively .

CTS TESTING RECORDS FOR EVALUATION OF R CURVE

The plane stress fractur toughness is found to be dependent on the plate thickness regardless of the rate of loading and temperature. Therefore it was intended to use, specimens with unified thickness equal to plate thickness being considered for actual service usage. The other dimensions and arrangements of the test piece are shown in fig(1). Five specimens of low strength steels were prepared with identical dimensions and initial crack length a_o and tested .
Displacement is plotted for each steel type p-u diagram, see fig(3). For each load increment equation (5) is applied to provide the new crack area (A) at each instant upto the point of instability load. Consequently for each displacement u and its corresponding crack area (A), direct substitution into

equation (8) will provide k_R value. The procedure is repeated for each point on the p-u plot up to the maximum attained load at which $k_R = K_c$. The 1.5 inch thickness specimens ensuring plane stress conditions for steel yield stress varies from 40-80 KSi are tabulated with its results in Table (1) .

Table (1)

Steel Type	Yield Strength σ_y in ksi	Fracture Toughness K_c in ksi/in	Charpy Value CVN in ft-lb	Critical C.O.D. δ_c mm	Crack length a_{cr} mm
A 36 Grade	36	314	45	0.270	13.65
A 572 Grade	50	395	50	0.411	17.50
A 302-B	56	237	61	0.448	20.06
A537-B	64	195	90	0.625	20.82
HY-80	80	276	72	0.516	18.76

The forementioned procedure is followed for theoretical evaluation of the R curve from the experimental load-displacement plot of the CTS. This method will save the time required for testing 10-15 specimens with different initial crack lengths for the various types of steel specimens. Fig.(4) shows an agreement of the theoretical R curve with that obtained experimentally for A572 grade steel by Novak(1). Typical R curve for various sized specimens of the A 572 steel tested at 72 f are compared with the evaluated R curve using the same thickness of 1.5 inch and dimensions in fig(1).

RESULT ANALYSIS AND DISCUSSION

The load displacement records are used for the evaluation of the crack growth resistance as a function of effective crack extension. Therefore the load-displacement data up to the critical opening displacement will be used through the math model to provide a record of the toughness development as the crack is driven stably under increasing loads. Typical R curves for various types of steels are evaluated from CTS of unified thickness, dimensions and at the same temperature and loading rate are shown in fig.(5). The above potential advantage of the C O D measurements is to relate δ_c to the critical size a_{cr} of elastic-plastic or fully plastic behaviou . The critical crack growth at the instability load is varies from (35.8% to 54.61%) of the initial crack size, for the five types of the steel tested. Moreover the critical crack size results obviously can be used to compare fracture toughness behaviour of different structural materials (4). Therefore fig(6) shows a δ_c-CVN(ft-lb) correlation for the five types of low strength steels, indicating that a general relationship between them is existed, although more tests are required and considerable scatter in results will be possible.

CONCLUSION

Load displacement of CTS plots are used for mathematical evaluation of the crack growth resistance. The development of the crack growth resistance, R curve concept for stable crack extension, offers considerable contribution to the subject of fracture toughness in plastic regions. Low strength, high toughness alloy steels with actual thicknesses used in practice will develop large scale crack tip plasticity. Thus the behaviour represented by plane stress intensity factor k_c will prevail. The R curve analysis is one of several extensions of the elastic plastic fracture mechanics. A single R curve needs a large number of direct k_c tests to be carried out with various initial crack lengths, a_o . In this paper one k_c test only is required for drawing the load-displacement plot accordingly for evaluation of R curve. Moreover the math model presented in this analysis proposed a relation between δ_c/ϵ_y and k_c/σ_y similar to that found by Egan(3) for the plane strain intensity factor k_{ic}. Equation (12) as a finder for k_c is represented in fig(7) and compared with that extrapolated for k_{ic} CTS yield a relationship for k_c performing plasticity in the form ,

$$\frac{\delta c}{\epsilon_y} = 0.381 \left(\frac{k_c}{\sigma_y}\right)^2 \qquad (13)$$

while experimental data extrapolated a relationship for k_{ic}, exhibiting a plastic behaviour as ,

$$\frac{\delta c}{\epsilon_y} = 2 \left(\frac{k_{ic}}{\sigma_y}\right)^2 \qquad (14)$$

Assuming two CTS specimensions with two different thickness to ensure plane stress and strain conditions are tested from the same kind of steel, preserving all other dimensions proportional to the thickness at fixed conditions of temperature and strain rate .
Therefore at the same strain level, δ_c will be merely equal in both specimens, and nevertheless the difference in C.O.D., the ratio between k_c/k_{ic} will be equal to 2/0.381 so $k_c = 2.29\ k_{ic}$ this result is confirmed from a wide experimentation carried out by Rolfe and Barsom (1) in the fully plastic behaviour of CTS, while a value of 10 was observed for linear elastic behaviour .

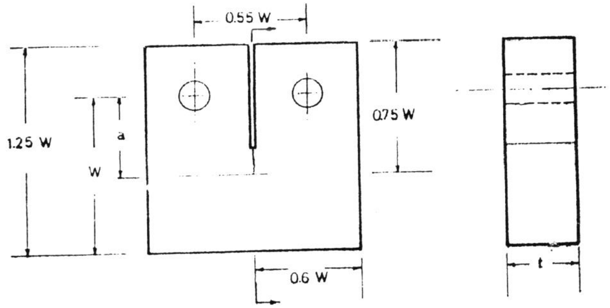
REFERENCES

1. Rolfe, S.T. Barsom, J.M.,
Fracture and Fatigue Control in Structures, Application of Fracture Mechanics,
Prentis-Hall, Inc., Englewood , Cliffs, N.J., 1977 .

2. Caddle, R.M.,
Deformation and Fracture of Solids,
Prentice-Hall Inc., Englewood, Cliffs, N.J.,1980

3. Egan, G.R.,
Compatability of Linear Elastic k_{ic} and General Tielding COD Fracture Mechanics .
Engineering Fracture Mechanics, 5,1973,pp 167-185.

4. Ayoub, M.T.
On The Relationship of Charpy Impact Results of Low Alloy Steel and its Fracture Toughness .
Proceeding of the International 85 AMSE Conference Modelling and Simulation , Athens, Greece, June 1984 .



a = t = w/2 = 1.5 inch

Fig.(1)-CT specimen used for Kc results

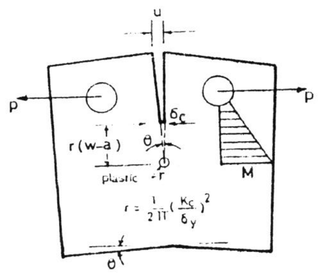


Fig.(2)- Schematic of math model applied to CT specimen under plane strain

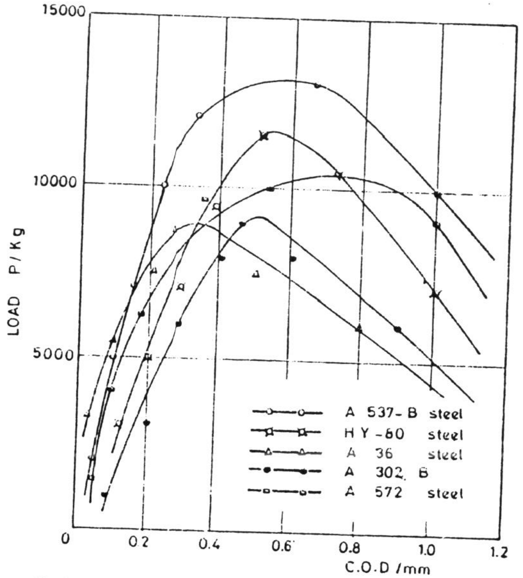


Fig.(3)_ Actual p - Δ plot for low strength steels of CTS

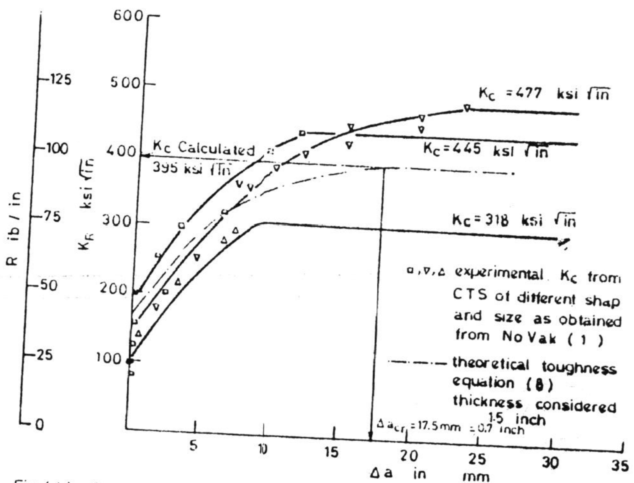


Fig.(4) – R curves for K_c experimental results and fracture toughness for A 572 Grade 50 Steel

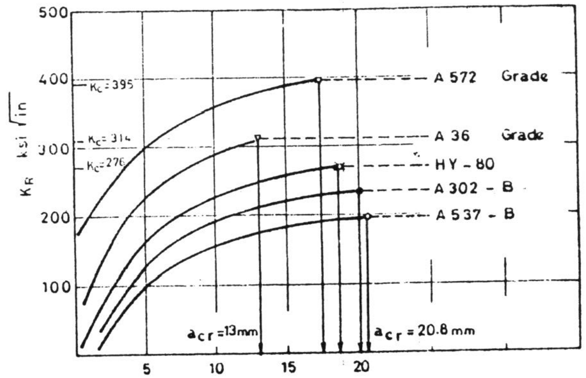


Fig.(5) – R curve evaluated for CTS thickness 1.5" for low strength steels

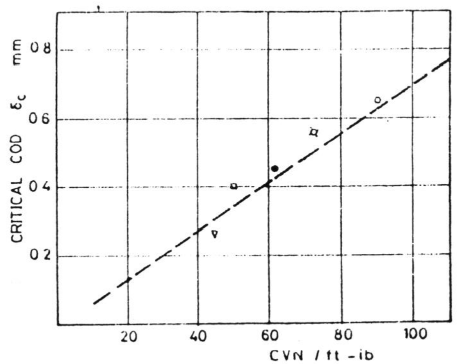


Fig.(6) – Critical crack opening / charpy energy for 5 types of steels