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Experimental and Theoretical Investigation on Notched Specimens Life Under Bending Loading

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***Abstract*—**In this work, bending fatigue life of notched specimens with various notch geometries and dimensions is investigated by experiment and Manson-Caffin theoretical method. In this theoretical method, fatigue life of notched specimens is calculated using the fatigue life obtained from the experiments for plain specimens (without notch). Three notch geometries including ∪-shape, ∨-shape and ⊔-shape notches are considered in this investigation. The experiments are conducted on a rotary bending Moore machine. The specimens are made of a low carbon steel alloy, which has wide application in industry. The stress- life curves are captured for all notched specimen by experiment. The results indicate that Manson-Caffin analytical method cannot adequately predict the fatigue life of notched specimen. However, it seems that the difference between the experiments and Manson-Caffin predictions can be compensated by a proportional factor.

***Keywords*—**fatigue life, Mason-Caffin method, notched specimen, stress-life curve.

I. INTRODUCTION

MOST of structures and engineering components have notches of various geometries such as the v-shape threads on nut-bolt connections, the square-shape key washer's grooves on shafts, scratches, nonmetallic inclusions and corners, fillets and geometry discontinuities, surface cracks in smooth structural components such as round bars, pipes and shells.

It is well recognized that notches cause locally high stresses. A sudden fracture will occur if the alloy cannot stretch to relieve such high stresses. The components are often subjected to dynamic loading which gives rise to reduction of fatigue life of the components. Tremendous efforts to study the effect of notches of various shapes and dimensions on fatigue life of engineering components under dynamic loading (axial, bending…) have been made [1]-[5].

There are numerous evidences in the literature that the presence of notch can reduce the fatigue life of components dramatically in some circumstances. The fatigue life of ∨-shape notch specimens under rotating bending by analytical method was examined [6]

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Reference [7] also shows some rotating bending test results and a comparison between analytical and experimental results. The experimental evaluation of fatigue life of notched engineering components is a cumbersome task and the results are always controversial and disputable. Reference [8] has proposed a new method in which the fatigue life of notched specimens is estimated from the fatigue life of plain specimens of the same material and geometry. The method, however, has been used only for ∪-shape notches.

This notch shape along with two other shapes including ∨-shape and square-shape notches are studied in this work and the applicability of the method to the two forgoing notch shapes is investigated. In this work, the theoretical Manson-Caffin method [8] is used for prediction of fatigue life of notched specimens with three notch geometries, (∪-shape, ∨-shape and ⊔-shape). The results are then compared with those reported in the literature [5].

II. MANSON-CAFFIN METHOD

With regard to the fact that predictions of fatigue life for notched specimens are based upon the Manson-Caffin theoretical method, the method is briefly reviewed in this section.

A. Local Stress

Suppose that a notched specimen is subjected to axial nominal surface strain amplitude of ε_n and its corresponding nominal stress of σ_n. K_f then indicates the reduction fatigue factor. The reduction factor is defined as the ratio between the fatigue endurance limit, σ_e, obtained for plain specimen and that measured for notched specimen. Neueber proposed a nonlinear elasto-plastic relation for fatigue loading as follows [9]:

$$K_\varepsilon K_\sigma = K_t^2 \tag{1}$$

Where K_ε, K_σ and K_t are the plastic strain, plastic stress and stress concentration factors, respectively. Also, σ and ε are the maximum local principal stress and its corresponding local strain, respectively at the root of notch (see Fig. 1). Equation (1) can be written as:

$$K_t^2 = (\sigma\varepsilon)/(\sigma_n \varepsilon_n) \tag{2}$$

The value of stress, σ , can be evaluated for elastic or elasto-plastic conditions as will be explained in the two next sub-sections.

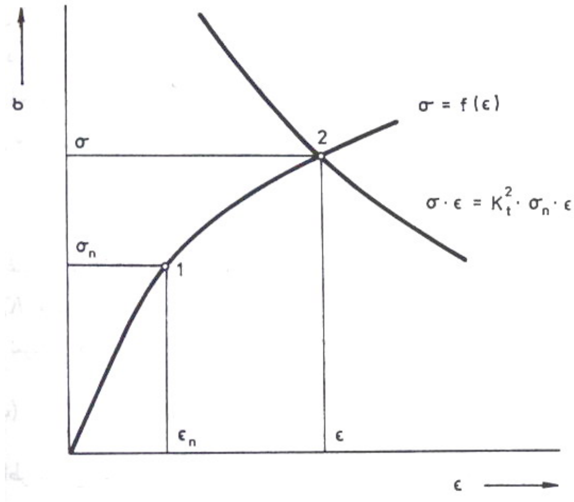


Fig.1 Schematic of Neueber law

B. Elastic Condition

If σ_n lies in elastic region in stress-strain curve, ε_n will be obtained using Hook's law as follows:

$$\varepsilon_n = \sigma_n / E \tag{3}$$

The cyclic stress-strain curve can be written as:

$$\varepsilon = \varepsilon_e + \varepsilon_p = \sigma/E + \left(\sigma/k\right)^{1/n} \tag{4}$$

In which n and k are materials constant, n is work hardening power and k is work hardening coefficient. Substituting (4) into (2) yields:

$$\sigma^2 + \left(E / k^{1/n}\right)\sigma^{1+\frac{1}{n}} - K_f{}^2 \sigma_n{}^2 = 0 \tag{5}$$

The value of σ is obtained from the solution of (5) providing σ_n and ε_n lie in elastic region of cyclic stress-strain curve.

C. Elasto-Plastic Condition

In the case, when nominal stress exceeds the yield stress, (2) can be written as:

$$K_\varepsilon = \varepsilon / \varepsilon_n = (\sigma / E + (\sigma / K)^{1/n}) / ((\sigma_n / E + (\sigma_n / K)^{1/n}) \tag{6}$$

The value of σ is obtained by using (6).

D. Life Prediction

The fatigue life of a notched specimen under bending fatigue loading is predicted by Manson's method [8]. Manson developed a relation to estimate the number of cycles for notched specimens as follows:

$$N_f = \left[N_f{}^{\varepsilon} - 4(N_f{}^{\varepsilon})^{0.6}\right] + 4(N_f{}^{\varepsilon_n})^{0.6} \tag{7}$$

Which N_f is life of notched specimen in rotating bending, $N_f^{\varepsilon_n}$ and N_f^{ε} are lives obtained from stress-life curves of plain specimen at the stresses of and σ, respectively [8].

III. Material And Specimens

A. Material

A low carbon steel alloy, Ck22, was used in this investigation. This type of steel alloy has wide application in industry. By using the universal testing machine, Instron, the engineering stress-strain curve of the materials was obtained. From the curve, the yield stress and the ultimate strength of the material were obtained as: σ_y=600MPa and σ_{ult}=730MPa, respectively.

B. Specimens

All notched cylindrical fatigue specimens were machined from the steel alloy rods. The cylindrical fatigue specimens were machined with various sizes of circumferential∨-notches, ∪-shape and ⊔ -shape. The gauge length of 100 mm and the ratio d/D=7/11 was kept constant for all notched specimens. D and d are the rod and notch root diameters, respectively. Also *a* is the distance between edges of notches in all kinds of notched specimens. The dimensions of the specimens are provided in table I and a schematic view of the specimen are shown in Fig. 2.

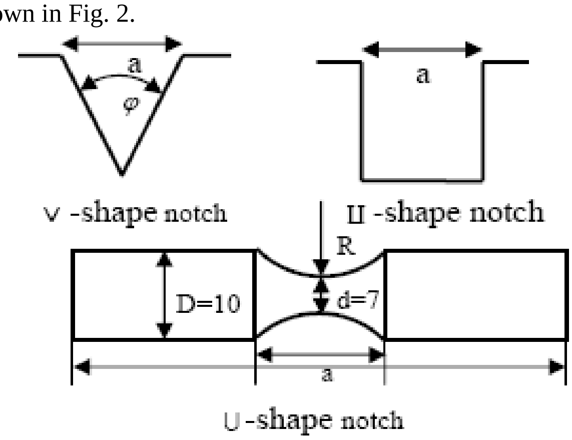


Fig. 2 Specimen's geometry used in this work

TABLE I
DIMENSION OF VARIOUS NOTCH SHAPES

∪ Shape		∨ Shape		⊔ Shape
***R* (mm)**	***a* (mm)**	*φ*	***a* (mm)**	***a* (mm)**
1	2	30^0	1	1
2	4	60^0	2.3	2
4	6.8	90^0	4	4
8	10.6	120^0	7	8

Stress concentration factor was obtained using finite element method and those available in the literature for all notch geometries [5]. The results are given in table. 2. For further details of the procedure for stress concentration determination see [5].

TABLE II
STRESS CONCENTRATION FACTOR FOR VARIOUS NOTCH SHAPES

∨ Shape	K_t	U Shape	K_t	Π Shape	K_t
Angle		R (mm)		a (mm)	
60	6.1	2	1.4	2	9.17
90	8.76	4	1.33	4	7.97
120	9.66	8	1.3	8	6.01

IV. RESULTS

A. Calculations of N and K

The stress-strain curve of the material (see Fig. 3) was obtained from tensile test conducted on plain specimens. The Hollomon stress-strain relation expressed as $\sigma = K\varepsilon^n$ was used for defining the stress-strain curve and consequently for identification of material constants (*n* and *K*). The constants were identified as *K*=850 MPa and *n*=0.0508. The evaluation of the fatigue life reduction factor, K_f, has fully been calculated for all notch geometries and the results have been given in [5]. A typical curve is illustrated in Fig. 4 which S-N curves for ∪-shape notched specimens are compared with that of a plain specimen.

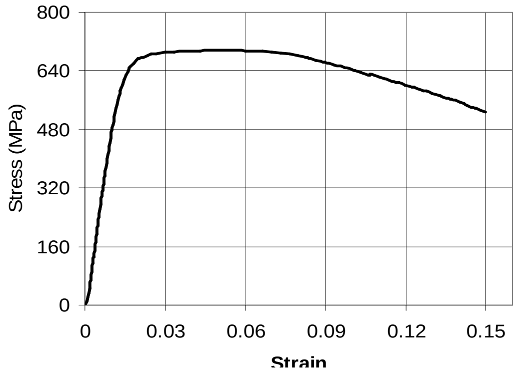


Fig.3 Stress-strain curve for CK22 steel

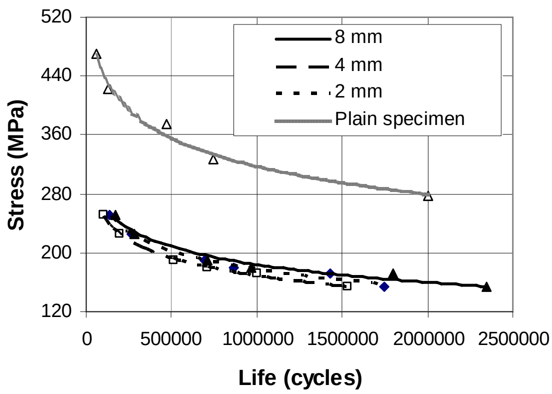


Fig. 4 S-N curves for ∪-shape notched specimens

B. Fatigue life predictions

Having known the values of *K*, *n* and E=200 GPa, the value of stress can be evaluated form (5) or (6) for elastic or elasto-plastic conditions, respectively. In the next stage, $N_f^{\varepsilon_n}$ and N_f^{ε} are determined from stress-life curve of plain specimen at the stresses of σ_n and σ, respectively. Finally, the life of notched specimen in rotating bending, N_f, is calculated from (7). The predicted and experimental variations of stress versus fatigue life for ∪-shape notches are depicted in Fig. 5.

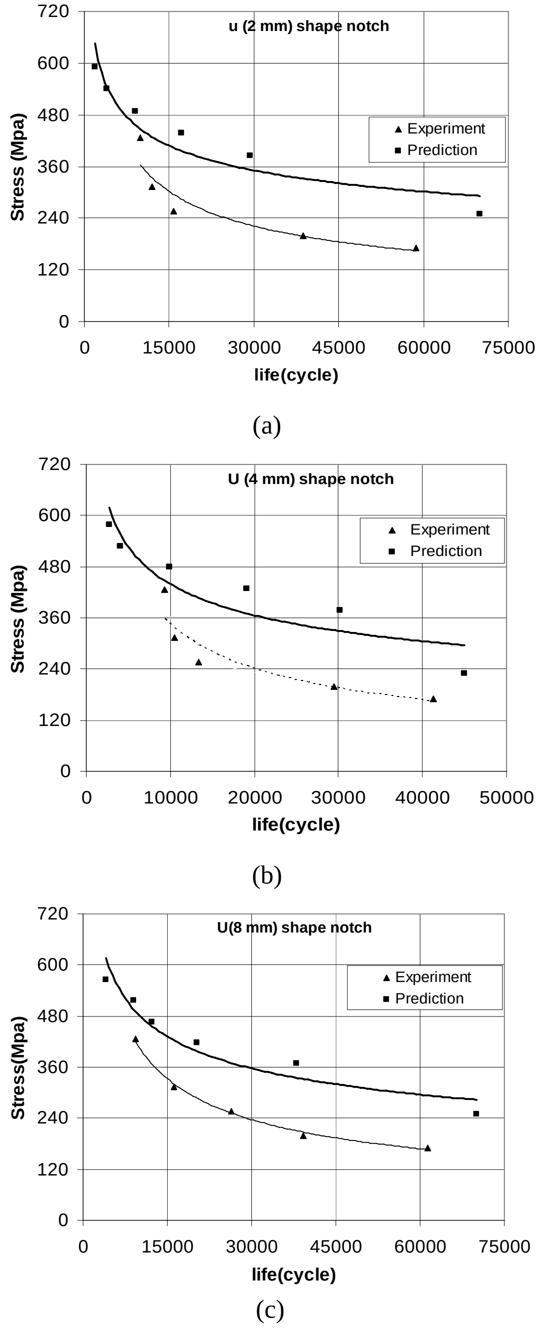
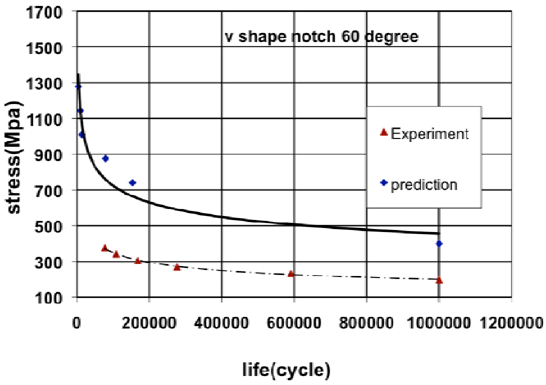
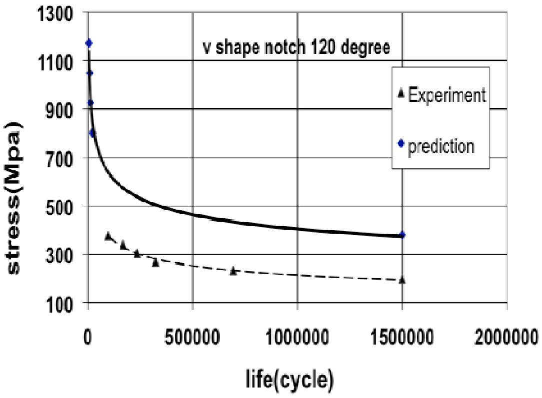


Fig. 5 Experimental and the predicted fatigue life for ∪-shape notch: (a) r=2 mm, (b) r=4 mm and (c) r=8 mm

As the Fig. 5 suggests, there is no good agreement between the experimental and calculated fatigue life for ∪-shape notches. However, it seems that the experimental and calculated curves differ by a proportional coefficient. The same trend can be seen more or less for ∨-shape notch results shown in Fig. 6 and for ⊔ -shape notches illustrated in Fig. 7.

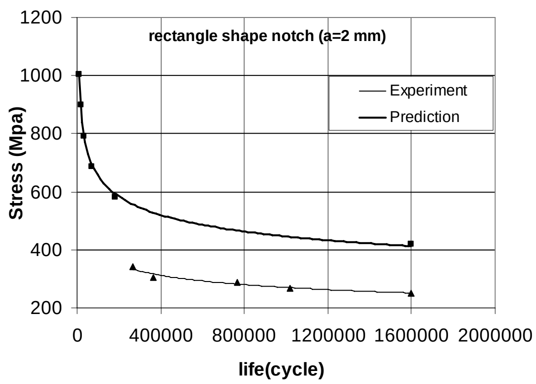


(a)

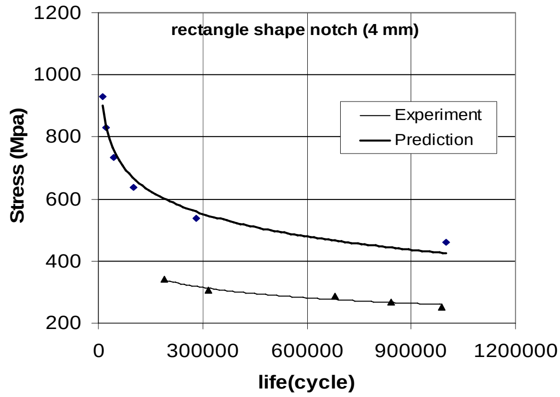


(b)

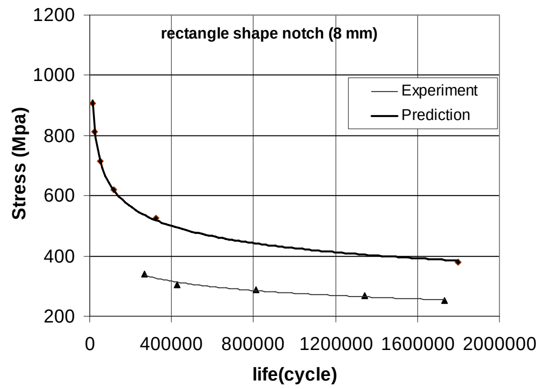
Fig. 6 A comparison between the experimental and the calculated fatigue life for ∨-shape notch: (a) 60^0, (b) 120^0



(a)



(b)



(c)

Fig. 7 A comparison between the experimental and the calculated fatigue life for ⊔ - shape notch:
(a) a=2 mm, (b) a=4 mm and (c) a=8 mm

V. Conclusions

In this work, bending fatigue life of notched specimens with various notch geometries and dimensions was investigated by experiment and Manson-Caffin analytical method. The coefficients *K* and *n*, which are required for evaluation of fatigue life of the specimens, were obtained by experiment. The fatigue reduction and stress concentration factors were adopted from the results reported in [5]. The results indicate that Manson-Caffin analytical method cannot adequately predict the fatigue life of notched specimen. However, it seems that the difference between the experiments and Manson-Caffin predictions can be compensated by a proportional factor. The value of this factor needs more experiments to be conducted and more notch geometries to be considered. This remains to be done in the next investigations.

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