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Effect of V Notch Shape on Fatigue Life in Steel Beam Made of High Carbon Steel Alloy AISI 1078

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Abstract: *The present work includes study effect of V notch shape with various angle orientation and depths on fatigue life behavior in steel beam made of High Carbon Steel alloy AISI 1078 which has a wide application in industry. Fatigue life of notched specimens is calculated using the fatigue life obtained from the experiments for smooth specimens (reference) and by use Numerical method (FEA).The fatigue experiments were carried out at room temperature, applying a fully reversed cyclic load with the frequency of 50 Hz and mean stress equal to zero (R= -1), on a cantilever rotating-bending fatigue testing machine. The stress ratio was kept constant throughout the experiment. Different instruments have been used in this investigation like Chemical composition analyzer , Tensile universal testing machine ,Hardness tester , Fatigue testing machine and Scanning Electron Microscope (SEM).The results show that there is acceptable error between experimental and numerical works.*

Keywords: *AISI 1078;V Shape Notch ; Stress Life approach ;Fatigue Life; S-N curve; FEA*

I. INTRODUCTION

Fatigue is an important parameter to be considered in the behavior of mechanical components subjected to constant and variable amplitude loading. Mechanical, metallurgical and environmental variables can influence the fatigue resistance of a structural component. Fatigue is the process of a cumulative damage in a benign environment that is caused by repeated fluctuating loads and, in the presence of an stress concentrators like notches and fillets.

In cyclic loading, the effect of the notch or the fillet is usually less than predicted by the use of the theoretical factors. The difference depends upon the stress gradient in the region of the stress concentration and on the hardness of the material [1]. A fatigue failure is one that occurs under cyclic or alternating stress of an amplitude that would not cause failure if applied only once. Fatigue is by far the most common cause of mechanical failure in engineering components; the prevention of fatigue failure is a major preoccupation of designers in many industries, such as such as power generation and

transport [2].The term "notch" in a broad sense is used to refer to any discontinuity in shape or non-uniformity in material 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, The failure usually originates in the formation of a crack at a localized point on the notches. Presentation of notches in structural components causes stress intensification in the vicinity of the notch [3], A. Fatemi, and Z. Zeng, [4] modeled fatigue behavior and life predictions of notched specimens made of QT and forged micro - alloyed steels ,they have been used notched circumferentially notched round bar and double-notched flat plate geometries, each with different stress concentration factors. Reference [5], described notch effects in fatigue and fracture and explained that the notch effect in fracture is characterized by the fact the critical gross stress of a notched structure is less that the critical net stress which acts on the remaining alignment are under notch tip, the notch effect in fracture is sensitive to structure geometry and the Wohler curve for the notched specimen is below the smooth specimen curve. Reference [6] developed experimental and theoretical life on notched specimens under bending. Fatigue life of notched specimens with various notch geometries and dimensions was investigated by experiment and Manson-Caffin analytical method. An experimental investigation was achieved by [7] , this study used cantilever rotating-bending fatigue testing machine to explain the effect of surface roughness on the fatigue life in steel alloy. 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 V -shape notch specimens under rotating bending by analytical method was examined [8]. Reference [9] also shows failure cycles of notched round specimens under strain controlled cyclic loading by using strain life relations obtained from experiment for plain fatigue round specimens. The maximum strain is computed by appropriate Finite element analysis using the FE software ABAQUS. They obtained that the total strain life curve generated from fatigue test of round specimen can also be used for the prediction of life for notched specimens based on actual strain developed at notch tip , the results shows that in most of the cases the predicted life is found to be less compared to experimental values for all the types of notched specimens.

II. FATIGUE METHODOLOGIES

There are three main approaches of fatigue methods which are, Stress life method , Strain life method and Fracture mechanics method. Number of cycles ranging from ($N \leq 10^3$) is considered as low cycle fatigue whereas ($N > 10^3$) cycles is considered as high cycle fatigue. In this work, we consider the Stress life approach to predict the cyclic life of specimens used for the rotational bending machine. This method is often referred to as infinite life design. Material properties from polished specimens are modified for surface conditions and loading conditions being analyzed. Stress concentration factors are used to account for locally high stresses. An effective stress concentration in fatigue loading is computed and an estimate of the fatigue life is determined by use ANSYS Workbench software and comparison between experimental and FEA results for different V shape angles and notch depths has been done.

Basquin's model

The stress-life curve is a graphical representation of fatigue data. It represents the relationship between fatigue life, in cycles, and the applied stress amplitude .Basquin's relation the most commonly used model and provides an analytical expression of the S-N curve, for finite life (low or high cycle fatigue). By use this technique an estimation of life prediction, with little information on the material, can be obtained , see [10].

The simple Basquin's curve is represented by :

$$\sigma_a = a \ {N_f}^b \qquad (1)$$

Where :

σ_a is the fatigue stress amplitude (MPa),

N_f is the number of cycles to failure (MPa),

The parameters a and b are both constant, depending on the material and on the geometry, respectively. The coefficient a is approximately equal to the tensile strength. The coefficient b is the fatigue strength exponent. These coefficients can be evaluated by use least square method (linearizing the power law in logarithmic form) ,it is important to mention that the S-N curve is represented in the log-log scale .

The value of Fatigue limit is not clearly obvious on the S-N curve; therefore, the Fatigue limit can be calculated by using the fatigue life estimation equation at 10^6 cycles.

Least Square Method

In many branches of applied mathematics and engineering sciences we come across experiments and problems, which involve two variables. For example, it is known that the Stress amplitude σ_a of a steel specimens in S-N curve varies with the Cycles of failure N according to the Basquin's formula $\sigma_a = a{N_f}^b$ Here a and b are the constants to be determined. For this purpose we take several sets of readings of stress amplitude and the corresponding Cycles. The problem is to find the best values for a and b using the observed values of σ_a and N, thus, the general problem is to find a suitable relation or law that may exist between the variables x and y from a given set of observed values,(x_i , y_i), $i = 1, 2,..........,n$. Such a relation connecting x and y is known as empirical law. For above example, $x = \sigma_a$ and $y = N$.

The process of finding the equation of the curve of best fit, which may be most suitable for predicting the unknown values, is known as curve fitting. Therefore, curve fitting means an exact relationship between two variables by algebraic equations. There are following methods for fitting a curve. The graphical method has the drawback in that the straight line drawn may not be unique but principle of least squares provides a unique set of values to the constants and hence suggests a curve of best fit to the given data. The method of least square is probably the most systematic procedure to fit a unique curve through the given data points.

III. EXPERIMENTAL WORK

The experimental work included assessment of fatigue life specifications by using stress life approach for High Carbon Steel AISI 1078 supplied from the local market with and without notches and the effect of angle orientation , depth of notch on the fatigue limit .The experimental procedure consist of four parts. The first one deals with the selection of materials used and the specimens preparation, the second part deals with different mechanical tests, the third includes details of fatigue test and finally the details of Microscopic inspection. A brief description for the different equipment used in this study had mentioned. For experimental work stages and the specimens distribution have been used in this work ,see [11].

3.1 Material Selection

In this work, high carbon steel alloy AISI 1078 treated commercially, was used in this investigation, this type of steel alloy has a wide application in industry. The chemical composition test of the alloy was done by use the device Spectrometer type (ARC. MET 8000), the results found within the standard specification limits as shown in table 1

Table. 1 : Chemical Composition of the AISI 1078

C%	Si%	Mn%	P%	S%	Cr%	Mo%	Ni%	Al%	Cu%	Fe%
0.773	0.236	0.327	0.006	0.012	0.16	0.002	0.069	0.04	0.062	Bal.

3.2 Mechanical Tests Tensile Test

The tensile test is a standard test which was conducted using the microcomputer controlled electronic universal testing machine type (WDW-100E - 100KN). The specifications of the tensile test have been restricted according to the ASTM [12], Tensile test results are given in table 1.They are presented as the mean value of five identical tests to satisfy an additional accuracy.

Table. 2 :Tensile Test Results of the AISI 1078

Property	Value
Tensile Strength σ_u (MPa)	675
Yield strength σ_y (MPa	510
Elongation [%]	15
Modula's of Elasticity (Gpa)	206

3.3 Hardness Test

Hardness is the property of a material that enables it to resist plastic deformation, usually by penetration. However, there are two tests have been done in this investigation Brinell's and Vicker's Hardness test. The average value of four readings was recorded ; the results are shown in table 3.

Table 3: Hardness Test Results

Property	Value
Brinell Hardness	200
Vickers Hardness (HV)	220

3.4 Roughness inspection

Surface roughness and surface integrity resulting from manufacturing processes are both important considerations in fatigue design. Fatigue damage on the surface of a component typically develops due to the surface integrity resulting from manufacturing, and the presence of stress concentrations originating from the surface topography. The specimens were first polished with different wet oxide aluminum papers by different degrees ,then followed by polishing with a string cloth soaked in alumina [13] . Once the manufacturing process of the specimens was done the surface roughness was measured by using a portable surface roughness tester type (SADT) and in order to reduce human errors during the measurement, the reading was taken for three times at different points and for all notched and smooth specimen. Then, the average and total surface roughness, R_a and R_t are calculated for both free and notched specimens and given in table 4.

Table 4: Values of surface roughness

Item	Ra [µm]	Rt [µm] max.
Free-Notch Specimen	1.75	3.25
Notched Specimen	1.85	3.31

1. Fatigue Test

a. Fatigue Test of Specimens

Fatigue specimens were machined in suitable dimensions to satisfy the requirement of the machine test that suited cylindrical specimens. Two types of fatigue specimens smooth and notched were prepared according to machine specifications. All the smooth and notched cylindrical fatigue specimens were machined from alloy steel with different content of carbon on a CNC lathe machine adopting standard manufacturing procedure and circumferential V notch shape angle of (30^0, 45^0&90^0) to a depth of notch was (0.5 & 2) mm respectively [14] with a notch radius as small as possible (< 0.075mm) [15] and was introduced at the portion of maximum bending. The geometry and a schematic view specimen are given in Fig. (2) .

b. Rotating Bending Machine

The fatigue behavior of different materials can be determined from laboratory tests. The type of fatigue testing machine is revolving fatigue testing machine type WP 140, (a single cantilever rotating bending model) with a constant amplitude (fully reversed bending). A rotating sample is clamped which on one side is loaded with a concentrated force with a maximum capacity of (0.3 KN) with constant frequency of (50Hz). A sinusoidal cyclic load with a stress ratio R = -1 (minimum load/maximum load) was applied throughout the experiment . As a result, an alternating bending stress is created in the cylindrical sample following a certain number of load cycles, the sample will rupture as a result of material fatigue. Tests were carried out at room temperature (20-24 °C) .The experiment was conducted by repeating so many similar procedure tests for all specimens. Bending moment values were used to determine the alternating bending stress, which can be determined directly from equation (6) .For constant amplitude load many parameters can be found ; for example: stress range, (Δ σ),a mean stress, σ_m, an alternating stress or stress amplitude, σ_a, and a stress ratio, *R*. Below some important relations used in the fatigue life analysis :

Stress range : $\Delta\sigma = \sigma_{max} - \sigma_{min}$ (2)

Mean stress: $\sigma_m = \frac{\sigma_{max}+\sigma_{min}}{2}$ (3)

Stress amplitude: $\sigma_a = \frac{\Delta\sigma}{2} = \frac{\sigma_{max}-\sigma_{min}}{2}$ (4)

Stress ratio: $R = \frac{\sigma_{min}}{\sigma_{max}}$ (5)

$M_b = F . a$ (6)

$W_b = \frac{\pi d^3}{32}$ (7)

By using the section modulus of the sample it is possible to calculate the alternating stress amplitude.

$\sigma_a = \frac{M_b}{W_b} = \frac{32\ F.a}{\pi d^3}$ (8)

$= 2\ F \quad MPa$ (9)

Where;

σ_a: Stress amplitude which is equal is the maximum alternating stress (MPa)

F : Applied Force (N)

a : bending arm = 106 ± 0.1 mm

d : diameter of the specimen = 8 ± 0.1 mm

M_b: bending moment (N.mm)

W_b:Moment of inertia (for hallow cylinder)

A series of tests was commenced by acting a specimen to the stress cycling, and the number of cycles to failure was counted. This procedure was repeated on other specimens at progressively decreasing stress amplitudes. Data were plotted as stress σ_a versus the logarithm of the number N of cycles to failure for each of the specimens. S-N curves are plotted by using software of Fatigue instrument present in PC which is connected directly to instrument as shown in Fig.(3).

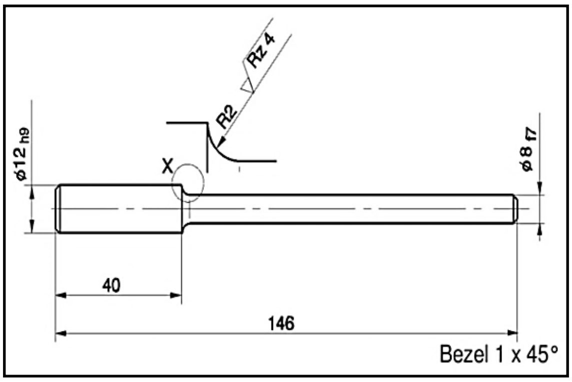


Fig. 2 Fatigue test specimens (mm)

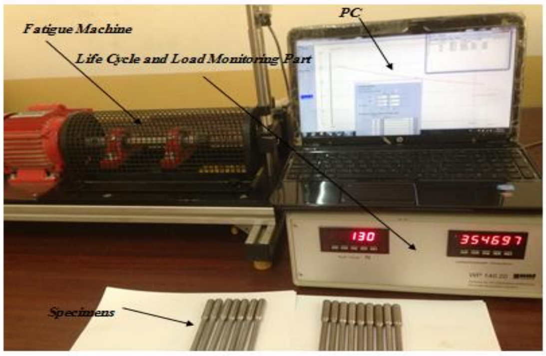


Fig. 3 Fatigue testing machine WP 140

IV. EXAMINATION FRACTURE FATIGUE

The process of achieve test fracture for the different fatigue specimens has been done to check the nature of fracture. Fracture surfaces of failed specimens have been analyzed using Optical Microscope (OM) and Scanning Electron Microscope Zeiss type (EVO 50) .Samples for microstructure examination were ground using different grades of wet silicon carbide papers (260, 500, 800, 1200 and 2000) , then the samples were polished using two type of alumina (0.5 micron and 0.3micron). Distilled water and alcohol were used to clean the samples in succession. Etching was carried out with naital (2 % HNO3) in alcohol followed by washing them with water and alcohol. Fig . (4) illustrates the photo digital system.

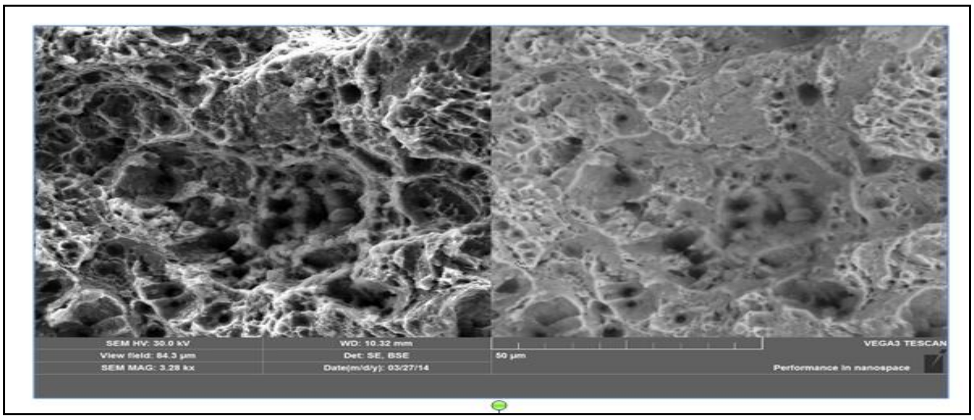


Fig. 4 Fracture surface of a specimen AISI-1078 tested by use SEM

V. NUMERICAL INVESTIGATION

The finite element method (FEM) is a powerful numerical procedure which can be used to obtain the solutions of a large number of engineering problems, especially in the area of solid mechanics [16]. In this work, FEM with the aid of ANSYS Workbench software was utilized for numerical analysis. A frequent tool used to illustrate the effect V notch Geometry on the fatigue performance in a structure element, verify the experimental results and to examine stress distribution at the fracture surface. Smooth and notched fatigue specimens with different notch orientation angles and two depths are modeled ,Solid hexahedral elements (solid185), with 8 nodes were considered. Constant amplitude fully reversed loading without any mean stress correction theory was applied to the structure. Also Fatigue analysis through ANSYS show that maximum value of stress occurs at the vicinity of change in cross section of the specimen where a V notch with different geometry present. Fig.(5) explain model with mesh ,boundary condition , maximum stresses and biaxiality generated in the model.

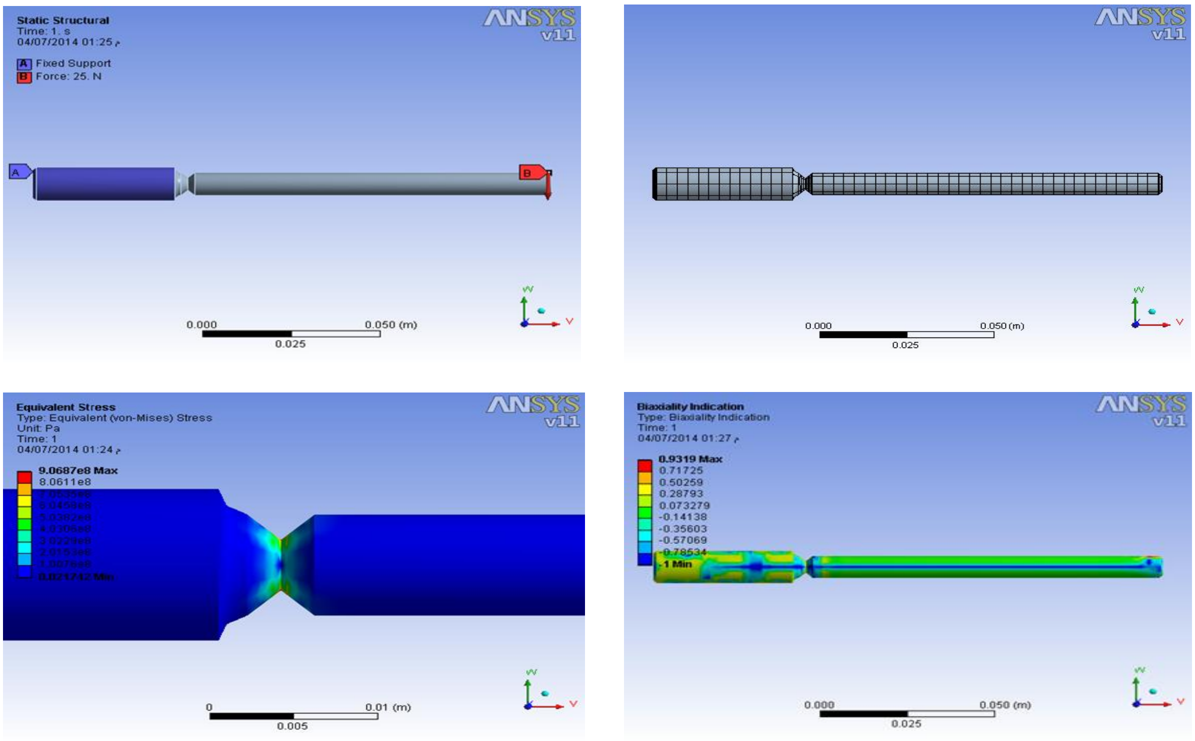


Fig.5 Shows Model with mesh, max. Equivalent stresses and Biaxiality for Notched bar

VI. RESULTS

In this work it is trailed to predict the fatigue life of notched fatigue specimens under effect of cyclic loading using stress life data of smooth fatigue specimen (free-notch) on the basis of maximum stress developed obtained from finite element simulated results of notched specimen under stress controlled cyclic loading . According to the accurate stress concentration factors corresponding bending stress can be found using least square method. Fatigue life equation and coefficients of Basquin's formula values have been found as shown in table 5. The radii of fillet at smooth specimen was found 2 mm ,while for notched specimens ,three angle orientation (30,45&90 degree) with two notch depths (0.5&2) mm were employed corresponding to which stress concentration due to bending (Kt) was found in table 6 , for more details of the procedure for stress concentration determination see [17]. For dynamic loading, we need to calculate Fatigue concentration factor K_f based on the notch sensitivity of the material as in below :

$$K_f = 1 + (K_t - 1)\,q \qquad (10)$$

$$q = \frac{1}{1 + \frac{a}{r}} \qquad (11)$$

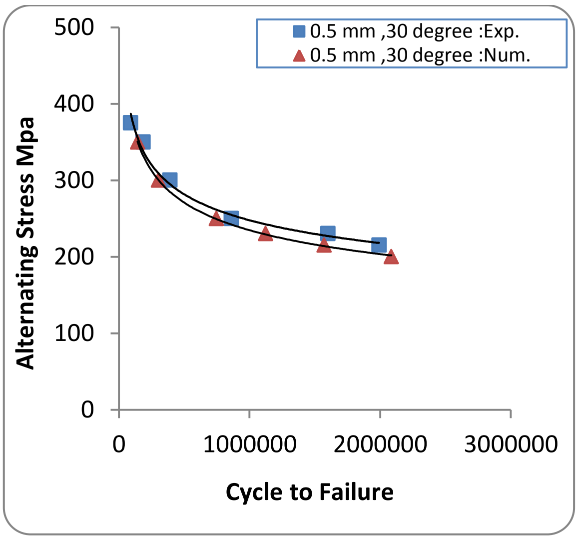
where q is the notch sensitivity it can be defined from the Kunn-Hardarth formula in terms of Neuber's constant (a) and the notch radius (r).

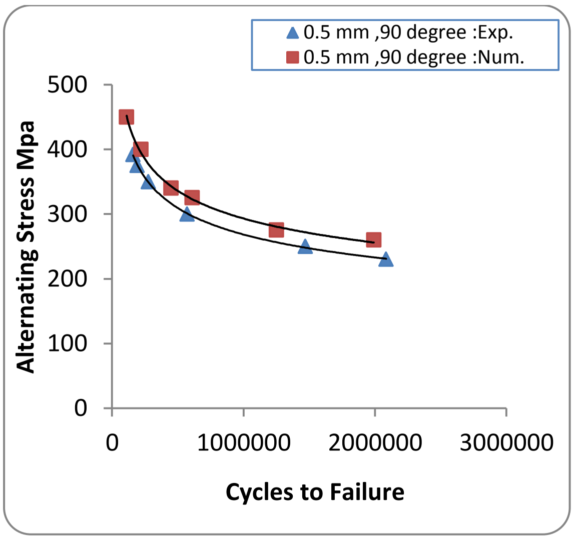
Table 5. Basquin's law parameters and correlation coefficients

Specimen type	$\acute{\sigma}_f$ (Mpa)	b	r
Smooth (reference)	5042.13	-0.197	-1
Notched ,h = 0.5 mm ,30°	3189.18	-0.185	-0.99
Notched ,h = 0.5 mm ,45°	4305.41	-0.2	-0.99
Notched ,h = 0.5 mm ,90°	4408.1	-0.196	-0.995
Notched ,h = 2 mm ,30°	2529.8	-0.188	-0.995
Notched ,h = 2 mm ,45°	2197.5	-0.173	-0.99
Notched ,h = 2 mm ,90°	2689.3	-0.183	-0.99

Table 6.: Values of Stress Concentration, fatigue and notch sensitivity factors

α °	h (mm)	r (mm)	K_t	q	K_f
30	0.5	0.07	4.28	0.298	1.98
45	0.5	0.07	4.15	0.301	1.95
90	0.5	0.07	3.47	0.299	1.74
30	2	0.07	3.95	0.301	1.89
45	2	0.07	3.83	0.300	1.85
90	2	0.07	3.23	0.300	1.67





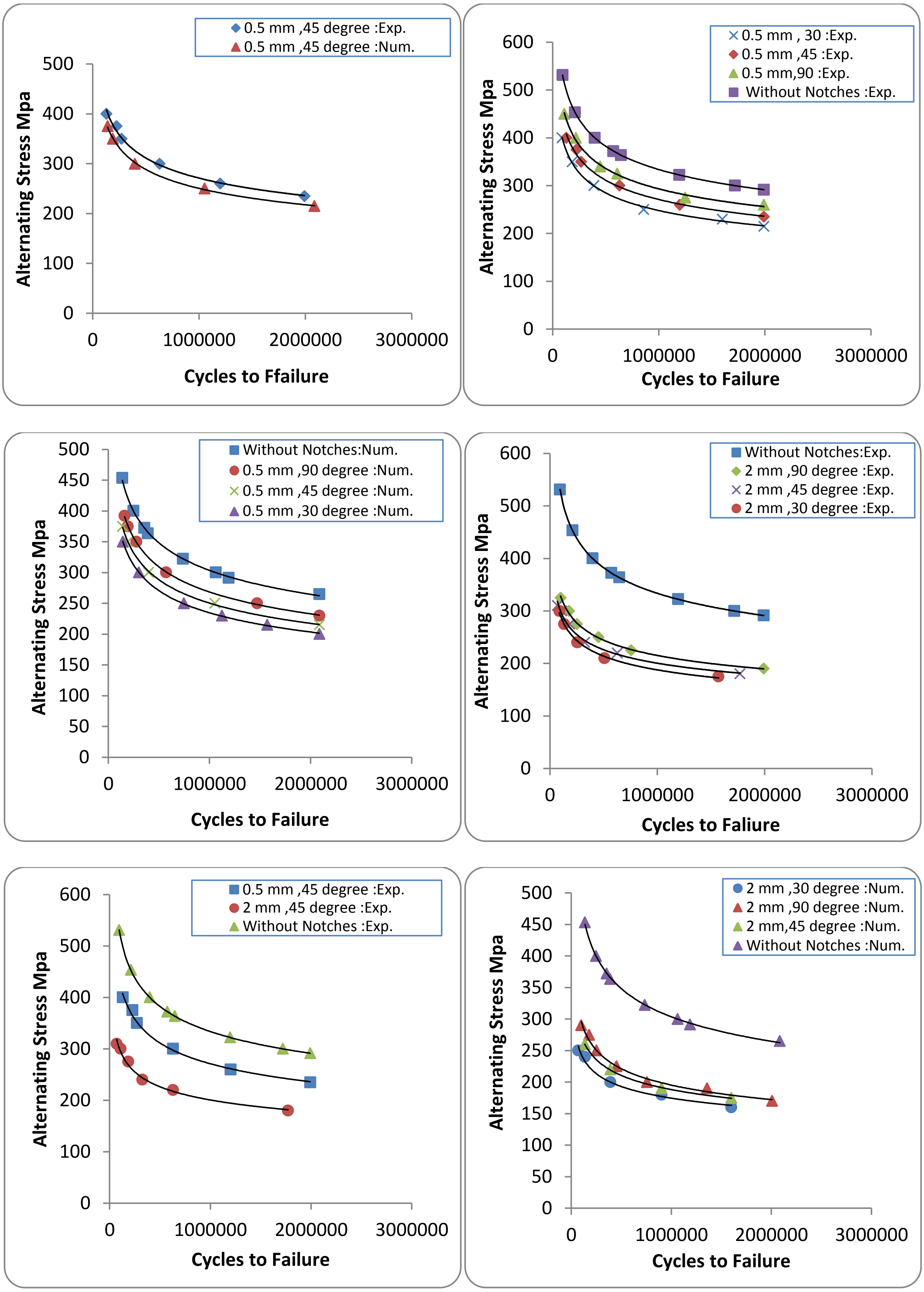


Fig. 6 Numerical and Experimental S-N curves for V notched Specimens with different angle orientation

VII. Conclusion

In this work, bending fatigue life of the specimens with V notch geometry of various angle orientation and notch depth was investigated by experiment and by FEA method . The Stress concentration factor is calculated analytically and numerically by use FEM. The results indicate that the FEA method is applicable to the experiments . From the results it is also observed that in most cases the predicted life is found to be less compared to experimental values for all the types of notched specimens. This may be due to the fact that the life has been predicted based on maximum stress in notched section [7] .The accuracy of the predicted life by FEA simulation depends on the selection of appropriate material model and the accuracy of the value of the material parameters used . It is very important to know that the prediction in this method depends on the correctness of the material total S-N curve (simple regression) generated from experimental results of high cycle fatigue data of cylindrical specimens. Good agreement between test and simulation data has been observed, the differences in results remains in range of13%.The common stress life curve generated from specimens of several notch angles gives a better prediction, which is apparent from the Fig.(6) . Stress concentration factor was obtained using finite element method and the results are given in table 6. Also the results show that maximum principle stresses is greater in small angle orientation while the fatigue limit will be more with the increasing of angle orientation.

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