# Effect of Stress Ratio and V Notch Shape on Fatigue Life in Steel Beam

Qasim Bader and Emad K. Njim

Abstract: Fatigue life experiments were performed on three steel alloys with different content of carbon weight (Low, Medium and High). Test results are obtained for constant amplitude load in rotating bending with four stress ratios of R = - 0.5 ,0, 0.25 and 0.5 and the specimens tested were with various notch geometries and dimensions. By using Stress Life approach, the two types cylindrical specimens smooth (reference) and notched have been investigated and the fatigue life analysis are obtained experimentally and by use FEA. Different instruments like Chemical composition analyzer, Tensile universal testing machine ,Hardness tester, Fatigue testing machine, Optical Light Microscope (OLM) and Scanning Electron Microscope (SEM) were employed in this investigation. The fatigue experiments were carried out at room temperature, on a cantilever rotating-bending machine. Based on experimental results the effect of stress ratio, R, is highlights on fatigue life and by use Numerical Investigation (FEA).The results show that the life of the specimen increased as the load ratio increased and there is acceptable error between experimental and numerical works.

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Keywords: V Notch, R ratio ,Stress life approach, Mechanical Tests ,Fatigue life, Stress Concentration Factor ,FEA

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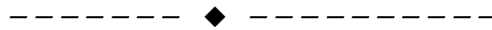
1. INTRODUCTION

It has been estimated that 90 % of all service failures of metal parts are caused by fatigue .Fatigue process undergoes several stages and from an engineering point of view it is convenient to divide the fatigue life of a structure into three stages [1]: fatigue crack initiation, stable crack propagation and unstable crack propagation. Generally mechanical components and structures contain geometrical discontinuities and notches. 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. In aircraft structures especially rotating parts require notches for their assembly by coupling. Stress concentration will be produced in these notches as a result of external force and depend on geometry. The stresses are generally higher than the nominal values, To assess the effects of notches on the behavior of structures, the prediction of fatigue strength compared to the challenges of design and safety is relevant. Fatigue life prediction of structures with, The failure usually originates in the formation of a crack at a localized point on the notches. It is known [2], that the stress ratio R (R = σ min / σ max) exert essential control over a fatigue crack propagation in samples and components working in fatigue stressing conditions. Thus influence of stress ratio R on the fatigue life under different loading ratio is most poorly studied. 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 tip [3]. The influence of load ratio, R, and loading mode on High cycle fatigue has been widely studied from both experimental and analytical [4]. Reference [5], shows influence the effect of load ratio and maximum stress intensity on the fatigue crack in Mild Steel. Reference [6] presented the effect of stress ratio and specimen thickness on fatigue crack growth of CK45 steel , Test results are obtained for constant amplitude load in tension with three stress ratios of R (0, 0.2 and 0.4) and different specimen thickness . Ref. [7], explained Stress Ratio and notch effect on fatigue crack initiation and propagation in 2024 Al-alloy ,it is found that for positive values of stress ratio, an increase in the R-ratio increase the number of cycles to initiate a fatigue crack while the alternating stress is not kept constant. This increasing is due to the diminution of amplitude loading range when maximum amplitude is maintained constant. Reference [8] , have been developed experimental and theoretical life on notched specimens under bending, fatigue life of notched specimens with various notch geometries and dimensions by experiment and Manson - Coffin analytical method. Reference [9] , 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.

2- EXPERIMENTAL WORK:

The experimental work included assessment of fatigue life specifications by using stress life approach for steel with different content of Carbon supplied from the local market with and without notches of various geometries , and effect of Stress ratio on Fatigue life .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 been mentioned.

2.1 MATERIAL SELECTION:

In this work, three steel alloys treated commercially, have been used in this investigation, those types of alloy has a wide application in industry. The chemical composition test of each alloy was done by use Spectrometer type (ARC. MET 8000), the results was within the specification limits and as shown in table 1.

Table 1:Chemical composition of tested materials (mass**%**)

Item	C	Si	Mn	P	S%	Fe
LCS	0.208	0.27	0.603	0.012	0.021	Bal.
MCS	0.369	0.303	0.738	0.009	0.023	Bal.
HCS	0.773	0.236	0.327	0.006	0.012	Bal.

2.2 MECHANICAL TESTS:

2.2.1-TENSILE TEST:

The tensile test is a standard test which was conducted using the microcomputer controlled electronic universal testing machine type (WDW-100E - 100KN , 2010) as shown in Figure (1), The load was applied at a constant rate of (2 mm/min) during all tests until failure of specimen occurred. The specifications of the tensile test have been restricted according to the American Society for Testing and materials specifications (ASTM) [10], at room temperature; the tensile specimen geometry and dimensions was prepared according to standards of ASTM A 370. Average value of four readings for the test have been taken to satisfy an additional accuracy; the results are given in table (2) .

Material	Property	Value
LCS	Tensile Strength σu (MPa)	470
	Yield strength σy (MPa	350
	Elongation [%]	26
	Modula's of Elasticity (Gpa)	202
MCS	Tensile Strength σu (MPa)	575
	Yield strength σy (MPa	480
	Elongation [%]	18
	Modula's of Elasticity (Gpa)	206
HCS	Tensile Strength σu (MPa)	675
	Yield strength σy (MPa	510
	Elongation [%]	15
	Modula's of Elasticity Gpa)	200
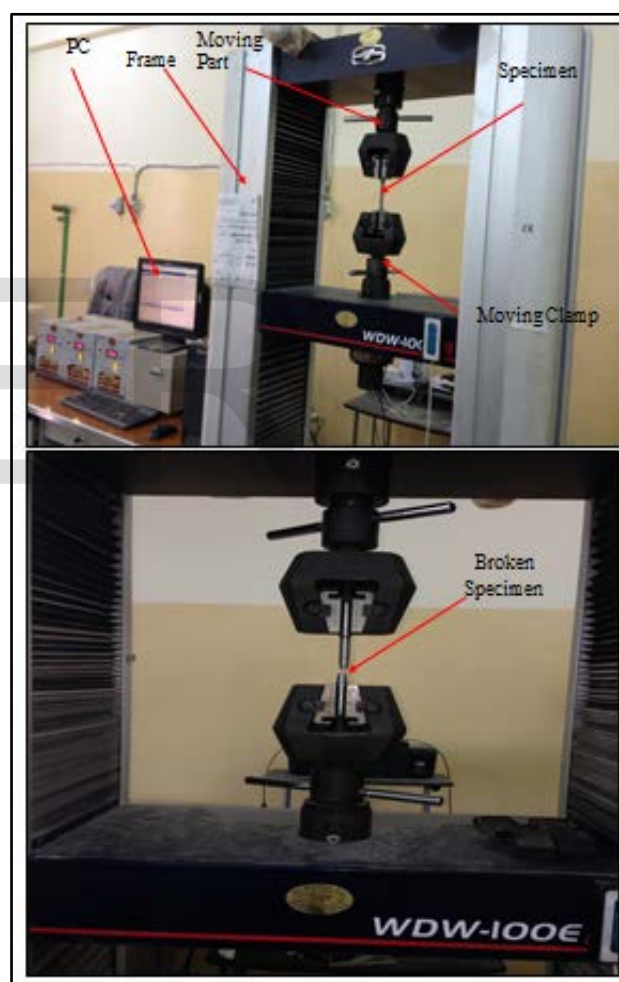
Fig. 1.Tensile testing machine

2.2.2 HARDNESS TEST :

Hardness is the property of a material that enables it to resist plastic deformation, usually by penetration. However, the term hardness may also refer to resistance to

bending, scratching, abrasion or cutting ; hardness test of a metal is generally performed to know is resistance against indentation and abrasion. Though there are two tests have been done in this investigation Brinell's and Vicker's Hardness test. The average value of three readings was recorded the results are shown in table 3.

Table 3: Hardness Test Results

Material	Property	Value
Low carbon steel	Brinell Hardness (HB)	135
	Vickers Hardness (HV)	142
Medium Carbon Steel	Brinell Hardness	172
	Vickers Hardness (HV)	180
High Carbon Steel	Brinell Hardness (HB)	200
	Vickers Hardness (HV)	220

2.2.4 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 [11] . Once the manufacturing process of the specimens was done the surface roughness was measured by using a portable surface roughness tester type (SADT) as shown in figure (2) 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 and summarized in table 4.

Table 4: Values of surface roughness.

Material	Ra [μm]	Rt [μm] max.
Low carbon steel	1.5	3.1
Medium carbon steel	1.75	3.25
High carbon steel	1.85	3.31
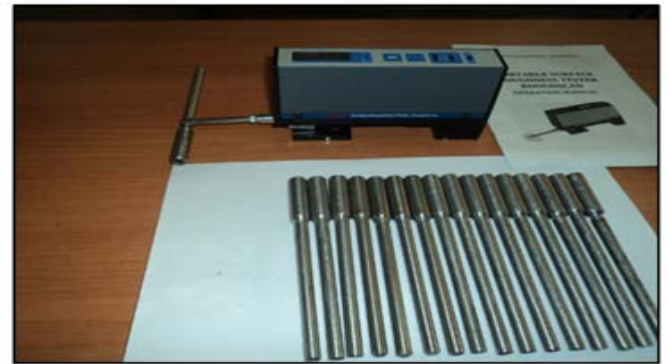
Fig. 2. Portable Surface Roughness Tester

2-3 Fatigue Test :

2-3.1. 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 by using a programmable CNC machine adopting standard manufacturing procedure and circumferential V notch of angle of (300, 450 and 900) to a depth of notch was (0.5) mm respectively [12] with a notch radius as small as possible (< 0.075mm) [13] and was introduced at the portion of maximum bending. A Grinding process has been done for the cylindrical fatigue specimens by use emery papers from Silicon Carbide with different ASTM grades , (#600,800,1000,1200,2000),then polishing process done by use Alumina solution with cloth, and the residual stresses were minimized by the heating process to (350) centigrade for one hour inside furnace and then cooling by air. The minimum diameter of each specimen was measured at positions around the circumference on a toolmaker's microscope at (30) magnification. Specimens having a variation of more than (0.05 mm) in diameter were discarded. The fillet radii of the stress concentration specimens were checked at the same time that the diameter was measured. The geometry and a schematic view specimen are given in Fig. (5) .

2.3.2 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 as shown in Fig.(4) ,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), and environmental humidity comprised between (54-58%). The machining process for all specimens was maintained as constant as possible in order to avoid significant variation in the surface polish. High temperature is expected at the narrow section when the specimen is tested under loading close to elastic limit. A cooling system with cool air was employed in the lab building to maintain the temperature in this zone below 100 °C in order to restrict the highest testing temperature. Under this condition, it is assumed that there is no variation in the specimen microstructure 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 (3) .For constant amplitude load histories can be represented by a constant load (stress) range, ($\Delta\sigma$); a mean stress, σ_m ; an alternating stress or stress amplitude, σ_a, and a stress ratio, R, as shown in Fig.(3).This related with many parameters which related to the fully reversed loading [14].

Constant stress range: $\Delta\sigma = \sigma_{max} - \sigma_{min}$ (1)

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

Stress amplitude: $\sigma_a = \dfrac{\Delta\sigma}{2} = \dfrac{\sigma_{max}-\sigma_{min}}{2}$ (3)

Stress ratio: $R = \dfrac{\sigma_{min}}{\sigma_{max}}$ (4)

The bending moment is calculated with the load and the lever arm as follows:

$M_b = F \cdot a$ (5)

$W_b = \dfrac{\pi d^3}{32}$ (6)

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

Where,

$\sigma_a = \dfrac{M_b}{W_b} = \dfrac{32\,F \cdot a}{\pi d^3}$ (7)

= 2 F   MPa   (8)

σ_a: 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)
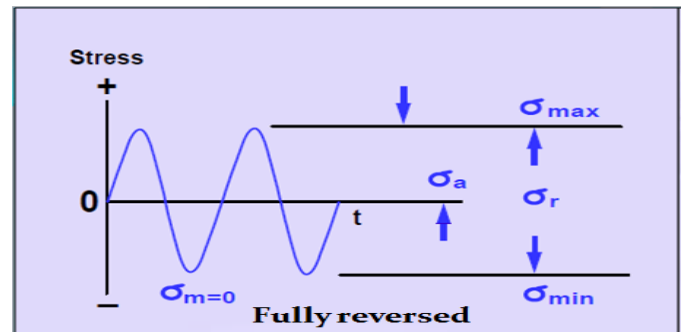W_b= Moment of inertia (for hallow cylinder)

Fig.3 : Fully Reversed Loading

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. It is important to know that each S-N curve obtained by this study has at least 8 specimens in both cases with and without notches. S-N curves are plotted by using software of Fatigue instrument presented in PC which is connected directly to instrument as shown in Fig.(5).
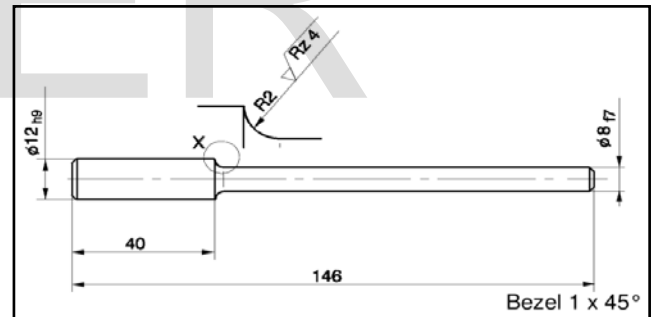

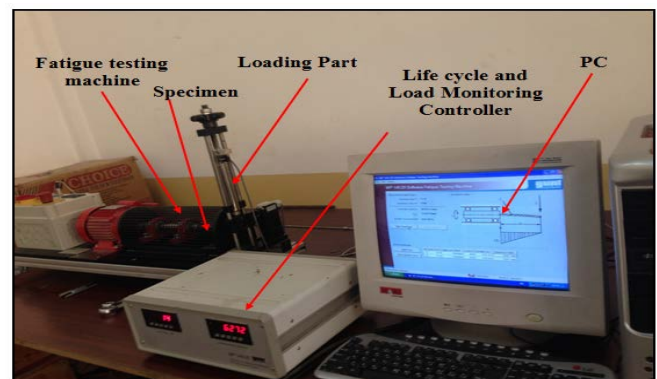**Fig. 4**: Schematic diagram for fatigue test specimens (mm)

**Fig. 5** : Fatigue testing machine WP 140

2.4 - 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 0.3 micron). 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. Figure (6) illustrates the photo digital system.
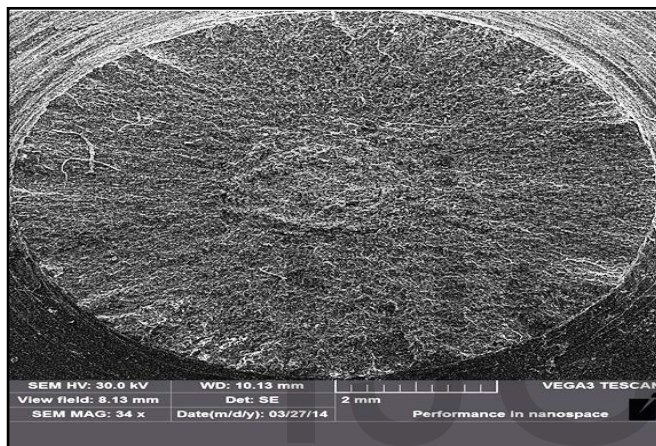

(a)
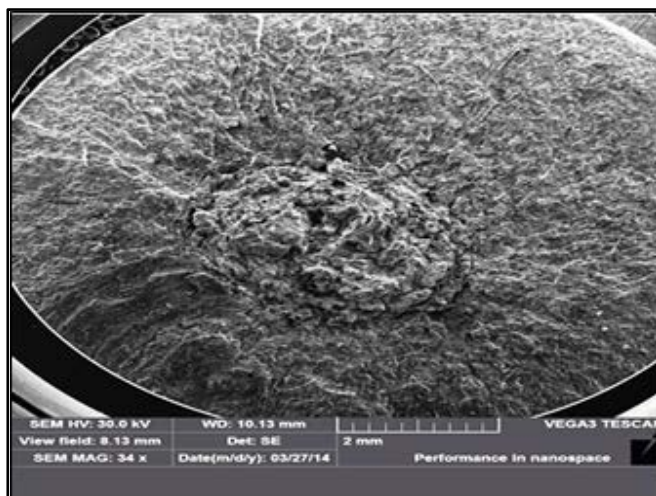
(b)

Fig. 6 : Fracture surface of a specimen AISI 1020 , (a)

without notches ,(b) with notches

3-NUMERICAL INVESTIGATION:

To examine stress distribution at the fracture surface, finite element method (FEM) was employed. ANSYS program was used for analysis to cross check the calculated values of stress. Stress analysis through ANSYS also show that maximum value of stress occurs at the vicinity of change in cross section of the shaft where a relief groove is present. Notched fatigue specimens with different notch angles and one depth are modeled and FE simulated results are generated for fatigue loading at different stress amplitude by using ANSYS program Version 11. The mechanical properties and Stress life data obtained by experiments .The element meshes were generated, boundary condition corresponding to maximum loading condition was given and stress analysis through ANSYS also show that maximum value of stress occurs at the vicinity of change in cross section of the shaft where a V notch with different geometry. Figure (7) explain model under boundary condition and maximum stresses generated in the model.
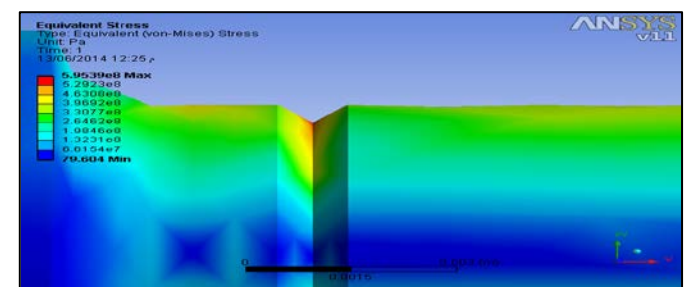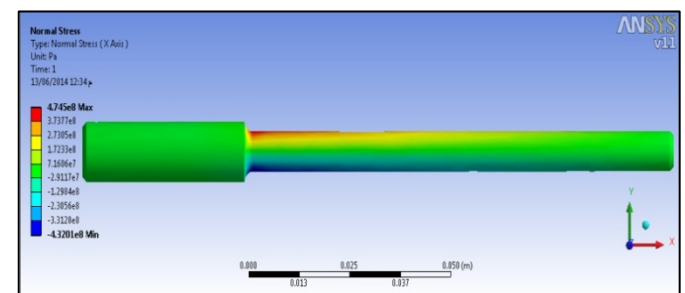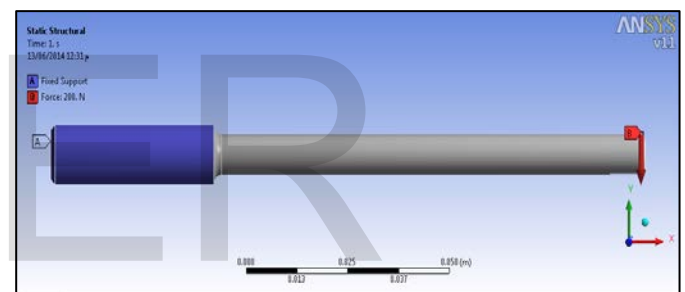
Fig. 7: Model and normal stresses for smooth specimen

and von - Mises stress for notched bar

4- RESULTS

- EFFECT OF V NOTCHES :

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 (without notch) on the basis of maximum stress developed obtained from finite element simulated results of notched specimen under stress controlled cyclic loading . The cylindrical specimen under consideration is being subjected to bending stress due to vertical component force, So as the shaft rotates there is a fluctuation of stress, the point which is subjected to maximum stress value is found and shown in Fig. (5). The various bending (σ nom) and at the failure surface is found. According to the accurate stress concentration factors corresponding bending stress can be found using least square method. The radii of fillet at smooth specimen was found 2 mm ,while for notched specimens ,three angle orientation(30,45 &90 degree) with one notch depth 0.5 mm were employed corresponding to which stress concentration due to bending (Kt) was found in table 5 , for more details of the procedure for stress concentration determination see [15]. For dynamic loading, we need to calculate Fatigue concentration factor Kf based on the notch sensitivity of the material as in below:

$$K_f = 1 + (K_t - 1)\, q \qquad (9)$$

where q is the notch sensitivity it can be defined from the Kunn- Hardarth formula in terms of Neuber's constant (a) , depends on the material strength and ductility and is obtained experimentally from long life fatigue tests on both notched and unnotched specimen and the notch radius r .For ferrous-based wrought metals, the constant a is given by:

$$q = \frac{1}{1+\frac{a}{r}} \qquad (10)$$

$$a \approx 0.001 \left(\frac{300}{\sigma_u(ksi)}\right)^{1.8} inch \qquad (11)$$

$$a = 0.001 \left(\frac{300}{0.5\ BHN}\right)^{1.8} inch \qquad (12)$$

- EFFECT OF STRESS RATIO

Fatigue life data collected experimentally and by FEA under constant loading conditions based on various load load ratios :R = (-1,- 0.5,0,0.25 ,0.5), these results are found for different content of carbon in steel alloy for smooth specimens and compared as explained in figure 12 . It is found that the maximum fatigue life of samples takes place

at R = 0.5, that corresponds to 10^6 cycles. With increase of Carbon content the Fatigue life will increase at the same Ratio and the increase of compressing stresses at the notch tip same influence, as well as increase of stretching stresses on the fatigue life of samples, i.e. reduces both fatigue life of samples and stage of crack propagation ,the results obtained is applicable with standard experimental results as shown in Figure (8). The fatigue Limit for different R load ratio is tabulated in Table 5.

Table 5:Values of Stress Concentration ,Fatigue and Notch Sensitivity Factors

| Mat.	R	S-N Equation	Fatigue limit (Mpa)
LCS	-1	σ = 3234.4 N - 0.195	218.672
	-0.5	σ = 4883.7 N - 0.204	291.574
	0	σ = 6892.6 N - 0.199	440.943
	0.25	σ = 9329.4 N - 0.2	588.645
	0.5	σ = 14783 N - 0.204	882.597
MCS	-1	σ = 3816.3 N - 0.195	258
	-0.5	σ = 5856.5 N - 0.204	349.65
	0	σ = 7895 N - 0196	526.443
	0.25	σ = 10520 N - 0196	701.48
	0.5	σ = 15823 N - 0196	1055
HCS	-1	σ = 4810.3 N - 0.2	303.5
	-0.5	σ = 7745 N - 0.213	408.339
	0	σ = 15758 N - 0.236	604.645
	0.25	σ = 16637 N - 0.217	829.994
	0.5	σ = 30711 N - 0.233	1228.27
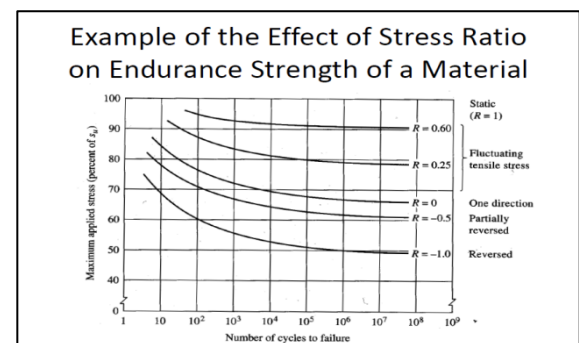
Fig. 8 : R values for common loading condition
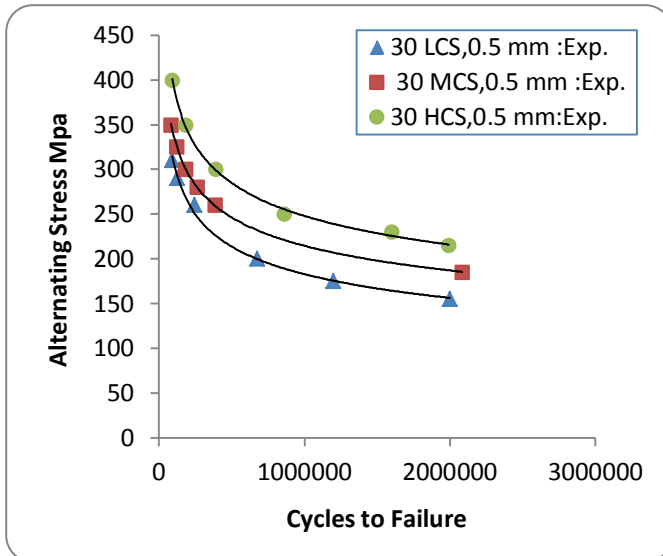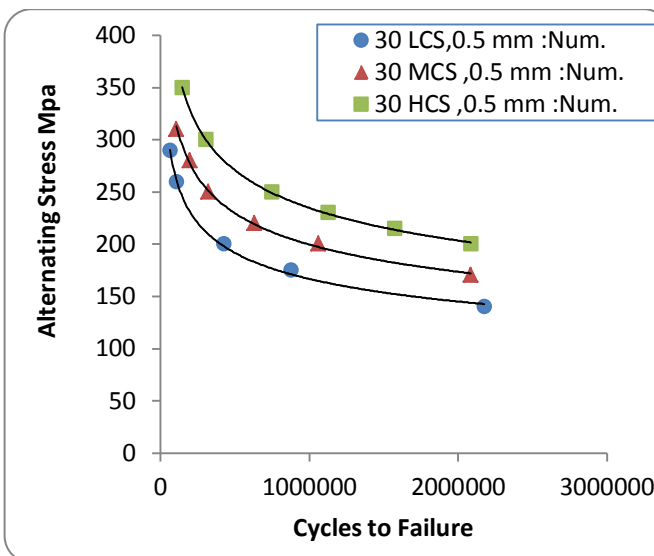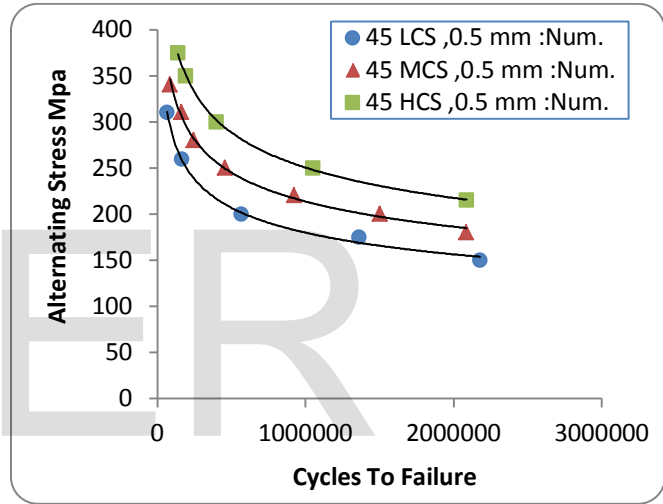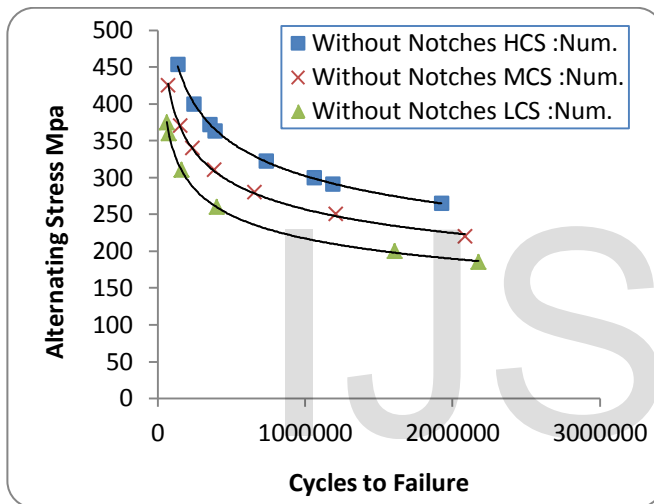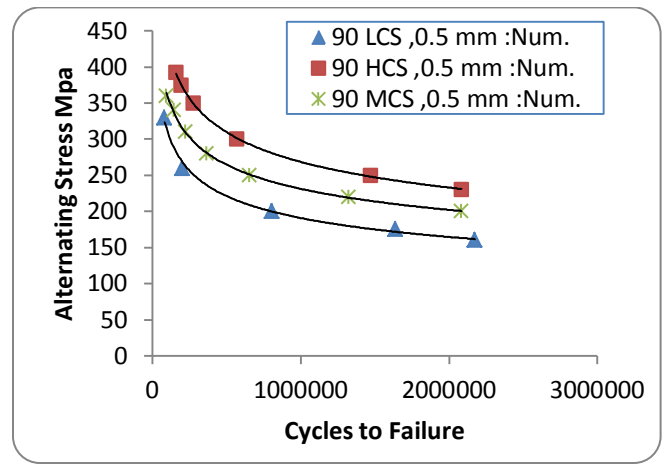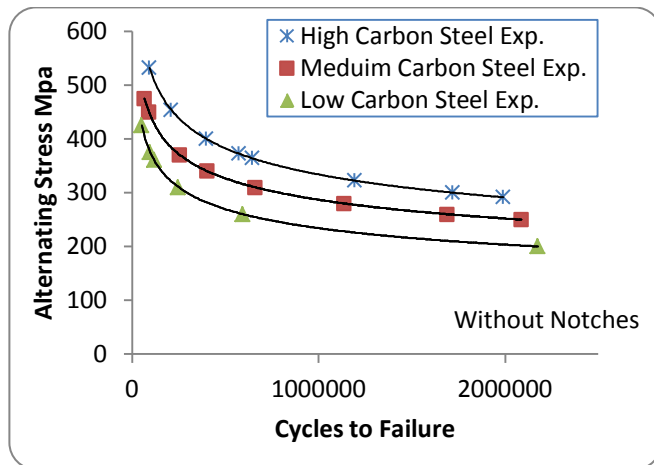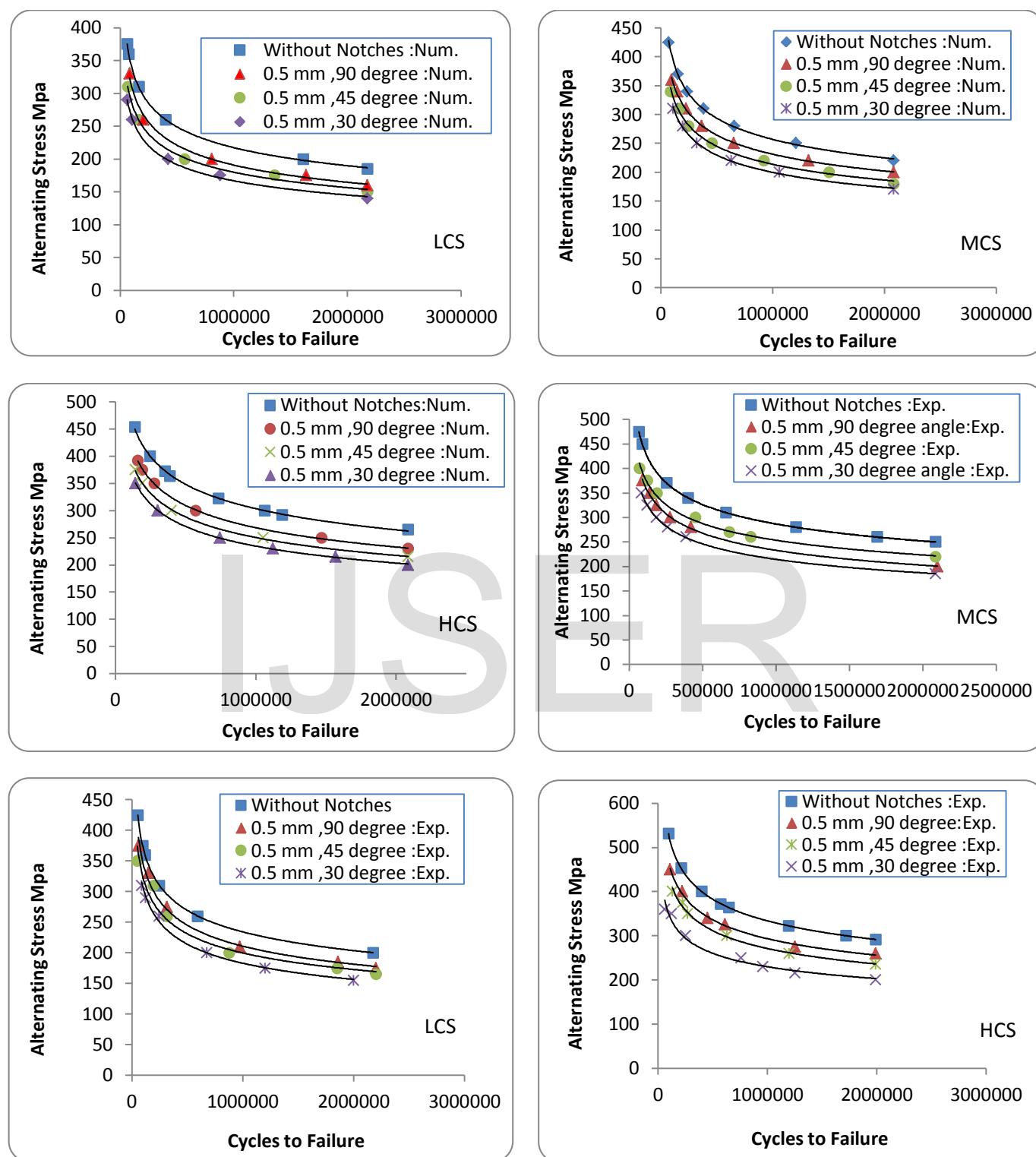
**Fig. 9** : Experimental & Numerical S-N curve for V Notched Specimens
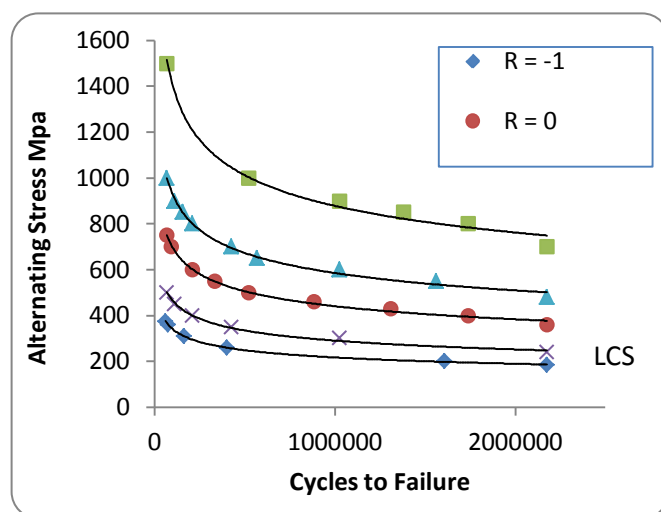
Table 6:Values of Stress Concentration ,Fatigue and Notch Sensitivity Factors

	α°	h (mm)	r (mm)	K_t	q	K_f
LCS	30	0.5	0.07	4.28	0.1643	1.54
	45	0.5	0.07	4.15	0.165	1.52
	90	0.5	0.07	3.47	0.1659	1.41
MCS	30	0.5	0.07	4.28	0.2682	1.88
	45	0.5	0.07	4.15	0.2698	1.85
	90	0.5	0.07	3.47	0.2672	1.66
HCS	30	0.5	0.07	4.28	0.2987	1.98
	45	0.5	0.07	4.15	0.3015	1.95
	90	0.5	0.07	3.47	0.2996	1.74
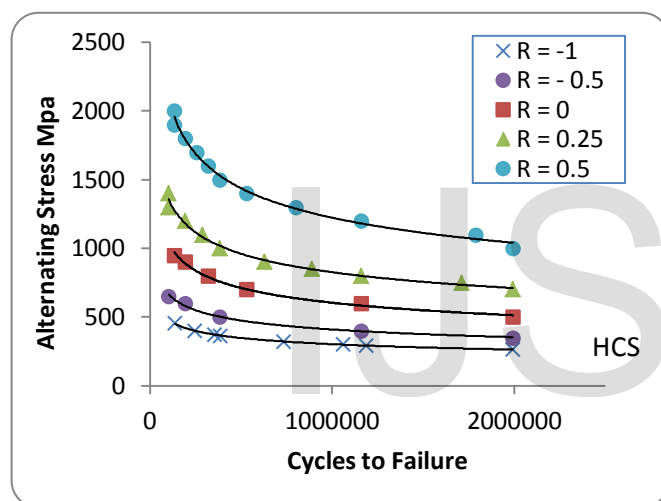
5- CONCLUSIONS:

In this work, bending fatigue life of notched specimens with V notch geometry of various angle orientation and notch depth was investigated by experiment and FEA method. The mathematical form of fatigue life equation of the specimens, were obtained by experiment and by use FEA. The Stress Concentration factor for the Geometry used in this work was calculated also analytically and numerically by use FEM. The results indicate the FEA method is applicable to the experiments .The final conclusion can be made from the results obtained that the S-N curve generated from fatigue test of round specimen can also be used for the prediction of life for notched specimens based on actual stress developed at notch tip. From the results it is also observed 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. This may be due to the fact that the life has been predicted based on maximum stress in notched section [9] .The predicted results fairly match with the experimental results. It is observed that the life prediction FEA simulation is acceptable for different stress amplitudes and also at different no. of cycles. 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 and the accuracy of simulated value of maximum stress of notched specimens .The maximum error between two methods found 9 %. The common stress life curve generated from several specimens gives a better prediction, which is apparent from the figures (9&10). Values of Stress
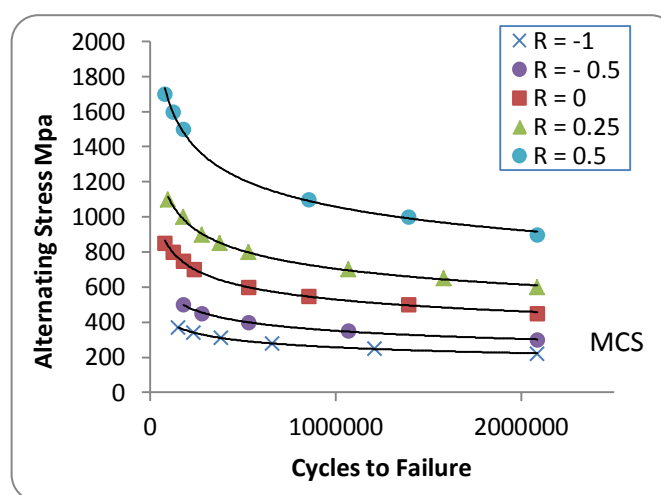
Fig. 10 : Comparison of S-N curve with different R ratios

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 increasing of angle orientation .

It is very important that the Fatigue limit value has strong relation with mechanical properties of metals ,so the increasing of the Carbon content in the metal will lead to increase in fatigue limit.

On the other hand it is concluded that for fatigue life equation represented by Basequen's form :

$$\sigma_a = aN_f{}^b$$

The coefficients a represent Stress-Life curve intercept and coefficient b is the fatigue strength exponent (Stress-Life curve slope). These coefficients after evaluated by linearizing the power law in logarithmic ,it is found that the increasing of R ratio will lead to increase a and reduce b ,for example load with load ratio , R= 0.5 ,a is the higher value and b is the lower value compared to other R load ratios and for any content of carbon used in this investigation.

ACKNOWLEDGMENT

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