

FATIGUE STRENGTH AND BEHAVIOUR OF
NOTCHED STEEL SPECIMENS

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This report is submitted in
partial fulfilment of requirement for the degree of
Bachelor of Mechanical Engineering (Structure and Materials)

Faculty of Mechanical Engineering
Universiti Teknikal Malaysia Melaka

MAY 2011

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NOTCHED STEEL SPECIMENS

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“I hereby declare that I have read this thesis and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering (Structure and Materials)”

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for the award of the degree of
Bachelor of Mechanical Engineering (Structure and Materials)”

Signature:

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Date:

Dedicated specially for
my beloved family

ACKNOWLEDGEMENTS

I would like to express my gratitude to my supervisor, Professor Madya Abdul Salam bin Mohd Tahir for his indispensable guidance and advice that he afforded me throughout the duration of this thesis. I am very much appreciating the time he has taken out of his busy schedule to offer helpful advice. Without his provision of supports, it would have been impossible to have this thesis completed.

I would also like to take this chance to apologise to my friends who I have intentionally ignored during the completion stages of this thesis. I will make it up to you later.

Finally, I would like to recognise the significant contribution of my family throughout the duration of my undergraduate degree. I genuinely appreciate their continual support. With their support, I have made this far.

Thank you again.

ABSTRACT

Fatigue is refers to the behaviour of materials under the action of repeated stresses or strain as distinguished from their behaviour under monotonic or static stresses or strains. Fatigue is the leading causes of failure in mechanical components and structures since they have been manmade structures or components. Fatigue has become progressively more prevalent as industries have developed various types of equipments that subjected to repeated loading and vibration. Fatigue failure is particularly insidious because it happened without any obvious warning. In this thesis, the material used is AISI 1020. A total of 24 specimens are prepared according to the specified design in ASTM standard for unnotched and notched specimens to compare their fatigue strength and behaviours. Certain machining process need to be done in order to prepare the specimen to the required dimension for the test specimens. The stress concentration factors applied to the notched specimen is defined and U-notch is chosen in this study. The fatigue test is conducted by using the INSTRON 8802 servohydraulic machine with its software and the test is run at low stress ratio ($R = 0.1$) and high stress ratio ($R = 0.5$). The data obtained from this study are plotted in the S-N curves and FDM of the materials. Based on the overall results, the fatigue strength for the unnotched specimens is higher than the notched specimens for both low and high stress ratio. Besides, the specimens conducted at high stress ratio also have higher fatigue strength and fatigue life. However, there are differences between the experimental and theoretical fatigue limits for the test specimens due to few factors which include effect of stress concentration, surface condition, stress parameters and etc. Finally, the faceted fracture surface is analysed as well as its relationship with the stress ratio and three different stages of crack propagation.

ABSTRAK

Kelesuan merujuk kepada sifat sesuatu bahan apabila ditindak dengan daya tegasan atau terikan yang berulang di mana sifat bahan ini berbeza apabila ditindak dengan daya tegasan atau terikan yang monotonik atau statik. Kelesuan adalah penyebab utama kepada kegagalan dalam komponen mekanikal dan struktur yang dibina atau dicipta oleh manusia. Kelesuan menjadi semakin meluas selari dengan teknologi di mana ia sering berlaku dalam komponen-komponen yang dikenakan beban atau getaran secara berulang-ulang. Kegagalan yang disebabkan oleh kelesuan adalah amat berbahaya kerana ia berlaku tanpa sebarang amaran. Dalam tesis ini, bahan yang digunakan adalah AISI 1020. Sejumlah 24 batang spesimen akan digunakan dalam kajian ini disediakan mengikut piawai dalam ASTM untuk membandingkan kekuatan kelesuan dan perilakunya. Beberapa proses perlu digunakan untuk menyediakan spesimen ujikaji dalam dimensi yang diperlukan. Faktor konsentrasi daya tegasan yang diterapkan dalam spesimen ditakrifkan dan U-lekuk dipilih dalam kajian ini. Ujian kelesuan ini dilakukan dengan mesin INSTRON 8802 dengan perisiannya dan ujian ini dijalankan pada nisbah daya tegasan rendah ($R = 0.1$) dan daya tegasan tinggi ($R = 0.5$). Data yang diperolehi dalam kajian ini diplot dalam graf S-N dan FDM. Berdasarkan keputusan secara keseluruhan, kekuatan kelesuan untuk spesimen tidak berlekuk adalah lebih tinggi untuk kedua-dua nisbah daya tegasan rendah dan tinggi. Selain itu, spesimen yang dijalankan pada nisbah daya tegasan tinggi juga memiliki kekuatan kelesuan yang lebih tinggi. Namun, terdapat perbezaan antara batas-batas kelesuan eksperimental dan teori spesimen ujikaji kerana beberapa faktor termasuk pengaruh konsentrasi daya tegasan, keadaan permukaan, daya tegangan dan sebagainya. Akhirnya, permukaan patah spesimen turut dianalisis.

TABLE OF CONTENTS

CHAPTER	TOPIC	PAGE
	DECLARATION	iii
	ACKNOWLEDGEMENTS	v
	ABSTRACT	vi
	ABSTRAK	vii
	LIST OF FIGURES	xi
	LIST OF TABLES	xiii
	LIST OF SYMBOLS	xiv
	LIST OF ABBREVIATION	xvi
	LIST OF APPENDIX	xvii
	CHAPTER 1	1
	INTRODUCTION	1
1.1	Background	1
1.2	Objectives	3
1.3	Scope	3
1.4	Problem Statement	4
	CHAPTER 2	5
	LITERATURE REVIEW	5
2.1	Cyclic loading	5
2.1.1	Constant Amplitude Loading	5
2.1.2	Variable Amplitude Loading	7
2.2	Definition of Fatigue	8
2.2.1	Fatigue Crack Initiation	9

2.2.2	Fatigue Crack Propagation	10
2.3	S-N Curve	11
2.4	Factors Affecting Fatigue	14
2.4.1	Stress Concentration Factor	15
2.4.2	Surface Finish Effect	18
2.4.3	Effect of Stresses	20
2.4.4	Effects of Environment	21
2.5	Fatigue Fracture Surface	21
CHAPTER 3		24
METHODOLOGY		24
3.1	Specimen Design and Specifications	24
3.1.1	Tensile Test Specimen	25
3.1.2	Fatigue Test Specimen	26
3.2	Number of Test Specimens	29
3.3	Test Material	30
3.4	Machining Process of Test Specimen	30
3.5	Experimental Apparatus	31
3.6	Tensile Test	32
3.6.1	Experimental Procedures	33
3.7	Fatigue Test	34
3.7.1	Experimental Procedures	35
CHAPTER 4		37
RESULT AND ANALYSIS		37
4.1	Tensile Test Results	37
4.2	Stress Concentration Factor	39
4.3	Fatigue Test Results	40
CHAPTER 5		53
DISCUSSION		53
5.1	Analysis of Tensile Test Results	53
5.2	Analysis of Fatigue Test Results	54

5.3	Factors Influencing Fatigue Test Results	55
5.3.1	Effect of Stress Concentration	56
5.3.2	Effect of Surface Condition	57
5.3.3	Effect of Stresses	58
5.4	Fracture Behaviour of Tested Materials	59
5.4.1	Fracture Behaviour of Materials under Tensile Test	59
5.4.2	Fracture Behaviour of Materials under Fatigue Test	60
	CHAPTER 6	66
	CONCLUSION AND RECOMMENDATION	66
	REFERENCES	69
	APPENDICES	A

LIST OF FIGURES

NO	TITLE	PAGE
Figure 2.1	Nomenclature for constant amplitude cyclic loading	7
Figure 2.2	Schematic ground-air-ground flight spectrum	8
Figure 2.3	Three stages of crack propagation curve	11
Figure 2.4	Typical S-N curve with a distinct fatigue limit	12
Figure 2.5	Comparison of S-N curve for ferrous and non ferrous metal	13
Figure 2.6	S-N curve for unnotched and notched 4340 steel components	14
Figure 2.7	U-notch of circular shaft	16
Figure 2.8	Stress distribution at the notch root	18
Figure 2.9	Effect of surface finish on the fatigue limit of steel	19
Figure 2.10	Fatigue fracture surface	23
Figure 3.1	Standard 12.5mm round specimen with gage length five times the diameter ($G = 5D$)	25
Figure 3.2	Specimens with continuous radius between ends	27
Figure 3.3	Specimens with tangentially blending fillets between the test section and the ends	27
Figure 3.4	Unnotched round specimens	28
Figure 3.5	U-notch round specimens	28
Figure 3.6	INSTRON 8802 Servohydraulic Universal Testing Machine	32
Figure 4.1	S-N curve for unnotched and notched specimen at low stress ratio ($R = 0.1$)	46
Figure 4.2	S-N curve for unnotched and notched specimen at high stress ratio ($R = 0.5$)	47
Figure 4.3	S-N curve for unnotched specimen at low and high stress ratio	48
Figure 4.4	S-N curve for U-notch specimen at low and high stress ratio	49

Figure 4.5 Fatigue Damage Map	52
Figure 5.1 Fracture at at the part between the test section and the end of the unnotched test specimen	57
Figure 5.2 Ductile fracture surface for unnotched specimen	60
Figure 5.3 Unnotched and U-notch specimen	61
Figure 5.4 Fractured notched specimen	61
Figure 5.5 Fracture surface of notched specimen	62
Figure 5.6 Macroscopic fatigue fracture surface	62
Figure 5.7 Fracture at notch region	64

LIST OF TABLES

NO	TITLE	PAGE
Table 2.1	Stress concentration factors for U-notch in a circular shaft	17
Table 3.1	Dimension of standard specimen	25
Table 4.1	Tensile test results for unnotched and U-notch specimens	38
Table 4.2	Chemical composition of AISI 1020	38
Table 4.3	Fatigue test result for unnotched specimen at low stress ratio ($R = 0.1$)	42
Table 4.4	Fatigue test result for U-notch specimen at low stress ratio ($R = 0.1$)	43
Table 4.5	Fatigue test result for unnotched specimen at high stress ratio ($R = 0.5$)	44
Table 4.6	Fatigue test result for U-notch specimen at high stress ratio ($R = 0.5$)	45
Table 4.7	Experimental and Theoretical Fatigue Limits	50
Table 4.8	Mean stress and stress amplitude for low and high test ratio	51
Table 5.1	Percentage of errors for fatigue limits	55

LIST OF SYMBOLS

NO	TITLE
S	Stress
N	Number of cycles to failure
S_m	Mean stress
S_r	Stress range
S_a	Stress amplitude
S_{max}	Maximum stress
S_{min}	Minimum stress
R	Stress ratio/ Radius of fillet
A	Alternating stress ratio
K_t	Stress concentration factor
σ_{max}	Maximum stress
σ_{nom}	Nominal stress
P	Force applied
D	Diameter of test section of specimen
h	Depth of notch
r	Radius of notch
k_s	Surface factor
G	Gage length
A	Length of reduced section
P_y	Yield load
P_{ult}	Ultimate tensile load
σ_y	Yield strength
σ_{ult}	Ultimate tensile strength
σ_{min}	Minimum stress

P_{\max}	Maximum load
P_{\min}	Minimum load
P_{mean}	Mean load
P_{amp}	Load amplitude
σ_f	Fatigue limit

LIST OF ABBREVIATION

NO	TITLE
FDM	Fatigue Damage Map
SCF	Stress Concentration Factor
FEM	Finite Element Method
ASTM	American Society for Testing and Materials
AISI	American Iron and Steel Institute
CNC	Computer Numerical Control
ISO	International Organisation for Standardisation
JIS	Japanese Industrial Standard
C	Carbon
Mn	Manganese
P	Phosphorus
S	Sulphur

LIST OF APPENDIX

NO	TITLE	PAGE
Appendix A	Flow Chart of Final Year Project	A
Appendix B	Gantt Chart of Final Year Project I	B
Appendix C	Gantt Chart of Final Year Project II	C
Appendix D	Detailed Drawing of U-notch Specimen	D
Appendix E	Detailed Drawing of Unnotched Specimen	E
Appendix F	Results of Tensile Tests	F
Appendix G	Sample Calculation	G
Appendix H	Physical Properties of Plain Carbon Steels and Low-Alloy Steels	H

CHAPTER 1

INTRODUCTION

1.1 Background

Mechanical failures have caused many injuries and financial losses. However, relative to the large number of successfully designed mechanical components and structures, mechanical failures are minimal.

Many different mechanical failure modes exist in all fields of engineering. These failures can occur in simple, complex, inexpensive or expensive components or structures. Stephen et al. (2001) stated that failure due to fatigue is multidisciplinary and is the most common cause of mechanical failure. Fatigue is a leading cause of failure in mechanical components and structures that are subjected to fluctuating stresses and strains which is below the yield stress. It may result in cracks or fracture after sufficient number of fluctuations. Fatigue on metal means that the metal will fail at much lower stress or formally known as repetitive loads and the metal will fail at much lower stress which the part can withstand under the application of a single static stress. Failure is the end result of a process involving the initiation and growth of crack, usually at the site of a stress concentration on the surface.

Fatigue failure is a result from the repeated applications of stress below the tensile strength of the material. The failure process consists of initiation of one or more cracks, the propagation of a dominant crack and final separation. Fatigue cracks usually initiate at the surface. Thus, the conditions of the surface and the environment are important factors influencing fatigue behaviours. Three basic factors are necessary to cause fatigue failure such as maximum stress, large enough variation or fluctuation in the applied stress and sufficiently large number of cycles of the applied stress. In addition, there are host of the other variables such as stress concentration, corrosion, temperature, overload, metallurgical structure, residual stresses and combined stresses which tend to alter the condition for fatigue.

Fatigue test can be thought of as simply applying cyclic loading to test specimen to understand how it will perform under similar condition in actual world or practice. The load application can either be repeated application of a fixed load or simulation of in-service loads. The material is subjected to repeated load cycles or fatigue in actual use. Engineers are faced with predicting fatigue life which is defined as the total number of cycles to failure under specified loading conditions. The closer the simulated analysis and testing are to the real product and its usage, the greater confidence in the engineering results.

Laboratory tests are essential in understanding fatigue behaviour and current studies with fracture mechanics test specimens are beginning to provide satisfactory design criteria. In 19th century, Wohler was the first to carry out extensive fatigue test programs on the test specimens rather than actual components and to use both rotating bending and axial loading test. Then, the plots of stress amplitude versus the log of number of cycles to failure or known as S-N curves are introduced.

Besides, the presence of a notch or hole will reduce the fatigue resistance but not as simply as a direct function of the notch stress concentration factor, the size of notch or hole is also need to be considered. It is important especially after the two crashes of de Havilland Comet passenger jets based on the study from the McEvily (2002). It was concluded that the crash had been due to failure of the pressure cabin at the forward Automatic Direction Finder window in the roof. The failure was a result of metal fatigue caused by the repeated pressurisation and depressurisation of

the aircraft cabin. Moreover, the supports around the windows were punch riveted, not bonded as the original specifications for the aircraft and the defect cracks created by imperfect nature of punch riveting caused the start of fatigue cracks around rivet. In addition, it was discovered that sharp cornered cut outs at the windows had higher stresses. Therefore, all future aircraft would feature windows with rounded corners to eliminating stress concentration. From the investigation, the sharp corners near the window opening acted as initiation sites for cracks. Since then, fatigue has been found at the root of failure of many mechanical components and stress concentration areas are important in determining the fatigue strength.

1.2 Objectives

The overall aims of this study are:

- 1) To determine and develop S-N curve and FDM (Fatigue Damage Map) of the test materials.
- 2) To generate useful information and data for the design of engineering components or structures based on the ‘stress-based’ concept or approach.

1.3 Scope

Based on the objectives mentioned above, the study is narrowed down to be more specific, in order to give a clearer view on the critical points. The scopes including in this study are:

- 1) To identify the suitable steel materials as available in store Faculty of Mechanical Engineering.
- 2) Design the test specimens for notched and unnotched conditions. Method of fatigue test, type and size of notches to be proposed based on the literature review.
- 3) To define the stress concentration factors (SCFs) applied to notched specimens either analytically or numerically (FEM).
- 4) To conduct fatigue tests to study the effects of stress ratios R, notch geometry and size.

- 5) Develop S-N curve and FDM of the test material.
- 6) Examine the faceted fracture surface (fractographic analysis) and establish its relationship with the effect of R- ratio and three different stages of the crack propagation.

1.4 Problem Statement

When a material is subjected to repeated loading and unloading, fracture is occurred. Microscopic cracks will begin to form at the surface if the loads are above a certain threshold and eventually a crack will reach a critical size and the structure will suddenly fracture. The shape of the structure will significantly affect the fatigue life. Sharp corners, grooves, key-holes or notches will lead to stress concentration where fatigue cracks can initiate. Therefore, stress concentration areas play important factors in determining the fatigue strength of the structure. Round holes and smooth transitions or fillets are important to increase or improve the fatigue strength of the structure as well as to eliminating the stress concentration of the part. Failure to control the geometries which included the notches and variation in cross section throughout a part will result in more severe damage of the object. Thus, the study of the fatigue strength and behaviour of notched steel specimens is important in this case.

CHAPTER 2

LITERATURE REVIEW

2.1 Cyclic loading

Mechanical components or structures are subjected to repeated load cycles. Most laboratory fatigue testing is done either with axial loading or in bending. Thus, it produced only tensile and compressive stresses. The stress usually is cycled either between a maximum and a minimum tensile stress or between a maximum tensile and a maximum compressive stress. There are two types of cyclic loading which are constant amplitude loading and variable amplitude loading.

2.1.1 Constant Amplitude Loading

Some practical applications and also many fatigue tests on materials, the cycling between maximum and minimum stress levels are usually maintained constant. Constant amplitude loading is used to obtain material fatigue behaviour for use in fatigue design. Nomenclature to describe test parameters involved in cyclic stress testing includes mean stress, S_m ; stress range, S_r ; stress amplitude, S_a ; maximum stress, S_{max} ; minimum stress, S_{min} ; stress ratio, R and alternating stress ratio, A . All the nomenclature is shown in Figure 2.1.

The mean stress, S_m is the algebraic average of the maximum and minimum stresses in one cycle.

$$S_m = \left(\frac{S_{max} + S_{min}}{2} \right)$$

The range of stress, S_r is the algebraic difference between the maximum and minimum stresses in one cycle.

$$S_r = S_{max} - S_{min}$$

The stress amplitude, S_a is one half the range of stress.

$$S_a = \frac{S_r}{2} = \left(\frac{S_{max} - S_{min}}{2} \right)$$

The maximum stress, S_{max} is the total of the means and stress amplitude in one cycle.

$$S_{max} = S_m + S_a$$

The minimum stress, S_{min} is the difference between the mean stress amplitude in one cycle.

$$S_{min} = S_m - S_a$$

The stress ratio, R is the ratio of the minimum stress to the maximum stress.

$$R = \frac{S_{min}}{S_{max}}$$

The alternating stress ratio, A is the ratio of the stress amplitude to the means stress.

$$A = \frac{S_a}{S_m}$$