

**EVALUATION OF CRACK GROWTH
BEHAVIOUR ON SANDWICH METAL PANEL
USING 2^k FACTORIAL METHOD**

ABDULLAH HELMI BIN ISAHAK

**MASTER OF SCIENCE
(MECHANICAL ENGINEERING)**

**UNIVERSITI PERTAHANAN NASIONAL
MALAYSIA**

2022

**EVALUATION OF CRACK GROWTH BEHAVIOUR ON SANDWICH
METAL PANEL USING 2^k FACTORIAL METHOD**

ABDULLAH HELMI BIN ISAHAK

A thesis submitted to the Centre for Graduate Studies, Universiti Pertahanan Nasional
Malaysia, in fulfilment of the requirements for the Degree of Master of Science
(Mechanical Engineering)

2022

ABSTRACT

This study investigates the crack growth response on sandwich metal panel (SMP) combination of high strength steel (HSS) as faces and magnesium alloy (AZ31B) as core on the light armoured vehicles LAV. Currently, LAV uses a special solid steel which content heavy material that causes the LAV reduce its lifespan performance and limit the movement after shot by ammunition bullets with high impact until the crack starts to form. The main objective of this research is to develop SMP that can provide improvement in terms of life durability compared to existing materials in LAV applications. A crack growth test was done using compact tension, CT by comparing the improvement solid HSS and AZ31B with sandwich metal panel in terms of life durability and energy absorption. Crack growth response investigation focuses on the frequency, $f = 10$ Hz and stress ratio, $R = 0.1$ as control variables. Next, the Design of Experiment of the 2^k factorial method was implemented by applying frequency, f (5 Hz and 10 Hz) and stress ratio, R (0.1 and 0.5) as statistical analysis. Twelve runs were carried out for the sandwich metal panel to obtain an optimum response for the number of life cycles and crack length in the empirical model equation and the best optimal D efficiency obtained. The increment of life cycle on crack growth analysis between HSS and SMP was about 18%, while the life cycle for AZ31B and SMP was about 34%. From the statistical result, an empirical model for the number of cycles has been chosen as optimum values for maximising the number of life durability on SMP at frequency, $f = 10$ Hz and stress ratio, $R = 0.5$. The increment of life cycle using optimum values between HSS and AZ31B with SMP was more than 60%. Thus, the potential of SMP to be replaced as an improvement in life durability for the light armour vehicle, LAV application has been verified.

ABSTRAK

Kajian ini mengkaji respon pertumbuhan retak pada panel logam sandwich (SMP) gabungan antara keluli berkekuatan tinggi (HSS) sebagai material lapisan luar dan aloi magnesium (AZ31B) sebagai lapisan teras pada kenderaan berperisai ringan, LAV. LAV kini menggunakan keluli pejal khas yang mengandungi bahan berat sebagai kandungan utamanya menyebabkan prestasi jangka hayat LAV berkurang dan pergerakannya terbatas selepas di tembak oleh peluru berkelajuan tinggi sehingga terjadinya retak. Objektif utama penyelidikan ini adalah untuk membangunkan SMP bagi menambahbaik material sedia ada pada LAV khususnya dalam aspek ketahanan jangka hayat. Ujian pertumbuhan retakan dilakukan menggunakan keluli ketegangan padat (CT), dengan membandingkan ketahanan jangka hayat dan serapan tenaga diantara bahan HSS dan AZ31B terhadap SMP. Respon pertumbuhan retakan dikaji dengan menetapkan nilai frekuensi, $f = 10$ Hz dan nisbah tegangan, $R = 0.1$. Rekabentuk eksperimen kaedah faktorial 2k telah menggunakan nilai f (5 Hz & 10 Hz), manakala R (0.1 & 0.5) pada analisa statistik. Sebanyak 12 ujian telah dijalankan terhadap SMP bagi mendapatkan bilangan jangka hayat dan panjang retakan yang optimum dalam model empirikal. Melalui kaedah ini, nilai optimum keberkesanan D diketahui. Peningkatan jangka hayat bagi analisis pertumbuhan retakan diantara HSS dan AZ13B terhadap SMP adalah sebanyak 18% dan 34%. Analisa statistik menunjukkan model empirikal kitaran jangka hayat telah dipilih dalam menentukan nilai optimum bagi maksimumkan jumlah jangka hayat terhadap SMP, iaitu pada nilai $f = 10$ Hz dan $R = 0.5$. Dapatan nilai optimum bagi peningkatan jangka hayat antara HSS dan AZ13B terhadap SMP melebihi 60%. Justeru, potensi SMP untuk menggantikan bahan LAV dalam meningkatkan jangka hayat berjaya dibuktikan.

ACKNOWLEDGEMENTS

In the Name of Allah, the Most Merciful and the Most Compassionate. All praise to Allah, the Lord of the world and peace be upon Muhammad, His servant and messenger, I managed to complete this project successfully. Firstly, I would like to express my sincere gratitude to my supervisor, Dr Mohamad Faizal bin Abdullah, for his invaluable advice, guidance, and encouragement throughout the preparation of this thesis. His profound knowledge and professional insight are of great value to me. His instructions are not only valuable on the research methodology but also on the truth in life mentor to the people now I am.

I would also like to thank my committee members, Mohd Khairul Faidzi bin Muhamad Paudzi, Dr Wan Yusmawati Wan Yusoff, Professor Dr Shahrum Abdullah and Dr Aidy Ali for his suggestions, discussions and encouragement going through the completion of this thesis. Thank you very much for always helping and guiding me in this project.

Special thanks are also given to my parents especially my beloved father and mother, Isahak Mat Lazim and Zaharah Ag. Hamat, for their love and support throughout my life. Also, my brothers and sisters, for all their support and motivation from the beginning until the end of this project. Their continuous love, care, encouragement, and patience are of utmost importance to me.

Last but not the least, I would like to thank everybody important to this thesis especially two important people in my project, Muaz Mubasyir and technician supporter, Nor Muhammad Azman Bin Sujani for their guidance as well as all individuals who have always provided their encouragement throughout my graduate career and contributed massively to the success of my project and academic Masters in Universiti Pertahanan Nasional Malaysia (UPNM).

This project cannot be done with supported by the Fundamental Research Grant Scheme, FRGS (grant no: FRGS/1/2018/TK03/UPNM/03/1).

Thank all of you so much.

APPROVAL

The Examination Committee has met on 27th Oct 2021 to conduct the final examination of Abdullah Helmi Bin Isahak on his degree thesis entitled ‘Evaluation of Crack Growth Behaviour on Sandwich Metal Panel Using 2^k Factorial Method’.

The committee recommends that the student be awarded the Master of Science (Mechanical Engineering).

Members of the Examination Committee were as follows.

Mejar Prof. Madya Ir. Dr. Hj. Razali Bin Abidin (B)

Faculty of Engineering

Universiti Pertahanan Nasional Malaysia

(Chairman)

Prof. Madya Dr. Ku Zarina Binti Ku Ahmad

Faculty of Engineering

Universiti Pertahanan Nasional Malaysia

(Internal Examiner)

Ts. Dr. Mahfodzah Binti Md Padzi

Faculty of Mechanical Engineering

Universiti Kuala Lumpur Malaysia France Institut

(External Examiner)

APPROVAL

This thesis was submitted to the Senate of Universiti Pertahanan Nasional Malaysia and has been accepted as fulfilment of the requirements for the degree of **Master of Science (Mechanical Engineering)**. The members of the Supervisory Committee were as follows.

Dr. Mohamad Faizal Bin Abdullah

Faculty of Engineering
Universiti Pertahanan Nasional Malaysia
(Main Supervisor)

Mohd Khairul Faidzi bin Muahamad Paudzi

Faculty of Engineering
Universiti Pertahanan Nasional Malaysia
(Co-Supervisor)

Dr. Wan Yusmawati Wan Yusoff

Faculty of Engineering
Universiti Pertahanan Nasional Malaysia
(Co-Supervisor)

Prof Ir. Dr. Shahrum Abdullah

Faculty of Engineering
Universiti Kebangsaan Malaysia
(Co-Supervisor)

Prof Dr. Aidy Ali

Faculty of Engineering
Universiti Pertahanan Nasional Malaysia
(Co-Supervisor)

UNIVERSITI PERTAHANAN NASIONAL MALAYSIA

DECLARATION OF THESIS

Student's full name : Abdullah Helmi Bin Isahak
Date of birth : 17th Jun 1995
Title : Evaluation of Crack Growth Behaviour on Sandwich Metal
Panel Using 2^k Factorial Method
Academic session :

I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged.

I further declare that this thesis is classified as:

- CONFIDENTIAL** (Contains confidential information under the Official Secret Act 1972)*
- RESTRICTED** (Contains restricted information as specified by the organisation where research was done)*
- OPEN ACCESS** I agree that my thesis is published as online open access (full text)

I acknowledge that Universiti Pertahanan Nasional Malaysia reserves the right as follows.

1. The thesis is the property of Universiti Pertahanan Nasional Malaysia.
2. The library of Universiti Pertahanan Nasional Malaysia has the right to make copies for the purpose of research only.
3. The library has the right to make copies of the thesis for academic exchange.



MOHAMAD FAIZAL ABDULLAH, Ph.D
Senior Lecturer
Department Of Mechanical Engineering,
Faculty Of Engineering,
National Defence University of Malaysia

Signature

**Signature of Supervisor/Dean of CGS/
Chief Librarian

IC/Passport No.

**Name of Supervisor/Dean of CGS/
Chief Librarian

Date:

Date:

Note: *If the thesis is CONFIDENTIAL OR RESTRICTED, please attach the letter from the organisation stating the period and reasons for confidentiality and restriction.

** Witness

TABLE OF CONTENTS

	TITLE	Page
	ABSTRACT	ii
	ABSTRAK	iii
	ACKNOWLEDGEMENTS	iv
	APPROVAL	vi
	APPROVAL	vii
	DECLARATION OF THESIS	viii
	TABLE OF CONTENTS	ix
	LIST OF TABLES	xii
	LIST OF FIGURES	xiv
	LIST OF ABBREVIATIONS	xvii
	LIS OF SYMBOLS	xviii
CHAPTER		
1	INTRODUCTION	1
	1.1 Background Research	1
	1.1.1 Application of Sandwich Metal Panel	4
	1.1.2 Potential of Core in Sandwich Metal Development	5
	1.2 Problem Statement	6
	1.3 Objectives	7
	1.4 Scope of Study	8
	1.5 Research Hypothesis	9
	1.6 Thesis Outline	10
2	LITERATURE REVIEW	11
	2.1 Introduction	11
	2.2 Expansion of Armor Vehicle Materials	12
	2.3 Acceptance Sandwich Metal Panel in Application	16
	2.3.1 Types of Sandwich Metal Panel	18
	2.3.2 Layer Configuration in Sandwich Metal Panel	22
	2.4 Fatigue Cycle Behaviour	26
	2.4.1 Cyclic Loading Assessment	27
	2.4.2 Low and High Cycle Fatigue	28
	2.4.3 Fatigue Limit	29
	2.4.4 Fatigue Life Calculation	30
	2.5 Crack Growth Behaviour	31
	2.5.1 Region in Crack Growth	32
	2.5.2 Types of Cracks	34
	2.5.3 Previous Study Related to Crack Growth	35
	2.6 Finite Element Analysis	39
	2.7 Design of Experiment (DOE)	40
	2.7.1 Taguchi Method	41
	2.7.2 Response Surface Method	41
	2.7.3 Factorial Method	42

	2.8 Summary	43
3	METHODOLOGY	43
	3.1 Introduction	43
	3.2 Selection of Materials for Testing	47
	3.2.1 High Strength Steels (HSS)	48
	3.2.2 Magnesium Alloy (AZ31B)	49
	3.3 Sample Preparation for Static, Fatigue, and Crack Growth	50
	3.4 Tensile Test Preparation	52
	3.5 Fatigue Test Preparation	55
	3.6 Sandwich Metal Panel Preparation	58
	3.7 Simulation Preparation	63
	3.8 Factorial Design Preparation for Number of Cycle and Crack Length	66
	3.9 Summary	69
4	RESULTS AND DISCUSSION	68
	4.1 Introduction	68
	4.2 Analysis of Tensile Test for HSS and AZ31B	70
	4.3 Analysis of Fatigue Behaviour	74
	4.3.1 Analysis of Fatigue Behaviour for HSS	76
	4.3.2 Analysis of Fatigue Behaviour for AZ31B	78
	4.3.3 Summary of Fatigue HSS and AZ31B for SMP Development	80
	4.4 Analysis of Crack Growth on HSS, AZ31B and SMP	81
	4.4.1 Crack Growth Analysis on HSS	82
	4.4.2 Crack Growth Life Analysis on AZ31B	85
	4.4.3 Crack Growth Analysis on Sandwich Metal Panel	88
	4.5 Simulation of Static Condition to Observe the Energy Absorption	91
	4.5.1 Tensile Test Underperforming Simulation	91
	4.5.2 Comparison the Tensile Test Simulation and Experimental	93
	4.5.3 Compact Tension Behaviour Using Simulation	95
	4.6 Selection of Sandwich Metal Panel	98
	4.7 Analysis of Crack Growth on Sandwich Metal Panel Using 2^k Factorial	100
	4.7.1 Analysis Optimisation of Number of Cycle for Sandwich Metal Panel	103
	4.7.2 Analysis Optimisation of Crack Length for Sandwich Metal Panel	108
	4.8 Validation optimum parameter using empirical model and experiment	113
	4.9 Summary	117

5	CONCLUSION AND FUTURE WORK	118
	5.1 Introduction	118
	5.1.1 Detailed characterisation of fatigue and crack growth behaviour of solid materials for HSS, AZ31B and sandwich metal panel SMP.	120
	5.1.2 Detailed optimisation number of cycles and crack length for sandwich metal panel and present the empirical model using 2^k factorial.	121
	5.1.3 Detailed validation empirical model of sandwich the metal panel in terms of crack growth responses with experiment	121
	5.2 Contribution to Knowledge	122
	5.3 Recommendations for the Future Work	122
	REFERENCES	124
	BIODATA OF STUDENT	135
	APPENDIX A	
	LIST OF PUBLICATION	136

LIST OF TABLES

TABLE NO.	TITLE	PAGE
Table 2.1	Type of sandwich panel development	19
Table 2.2	All-metal sandwich panels classified by the geometry of the core	20
Table 2.3	Hybrid metal sandwich panel combination of metallic and non-metallic	21
Table 2.4	Composite sandwich panel on fibre-matrix combinations	22
Table 2.5	Geometrical parameters of case studies	23
Table 2.6	High Strength Steel as faces development in sandwich panel	24
Table 2.7	Paris law constant, C, and m, for the SMSP and SAMSP	36
Table 3.1	Percentage of element composition in HSS	47
Table 3.2	Percentage of element composition in AZ31B	47
Table 3.3	Trend of S-N curve on sample of fatigue test runs for HSS and AZ31B	57
Table 3.4	Tensile test simulation outline	64
Table 3.6	Energy absorption simulation outline	65
Table 3.6	Experimental Ranges and Levels of Independent Variables	66
Table 3.7	Outcome design matrix of factorial design	68
Table 4.1	Tensile Test Result for HSS and AZ31B material	72
Table 4.2	Comparison the material properties HSS between experiment and standard values ASTM	73
Table 4.3	Comparison the material properties AZ31B between experiment and standard values ASTM	73
Table 4.4	Data experiment fatigue for High Strength Steel	77
Table 4.5	Data experiment fatigue for Magnesium Alloy, AZ31B	79
Table 4.6	List of three crack growth specimens taken before and after crack growth testing	81
Table 4.7	Results of specimens 3 of crack growth behaviour on HSS	82
Table 4.8	Results of specimen 3 of crack growth behaviour on AZ31B	85
Table 4.9	Results of specimen 3 of crack growth behaviour on sandwich metal panel	88
Table 4.10	Summary of energy absorption analysis on three different specimens with the same load and thickness	97

Table 4.11	12 runs of sandwich metal panel for two main factors against two main responses	101
Table 4.12	Analysation Number of Cycle for Empirical Model	107
Table 4.13	Analyzation Crack Length Value for Empirical Model	112
Table 4.14	Summarize the optimum parameter for SMP against the empirical number of cycles and crack length	114
Table 4.15	Results validation of crack growth on SMP using selected optimal values	115

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
Figure 2.1	Trend light armoured vehicle materials in reducing the weight	13
Figure 2.2	Latest armoured vehicle AV8 Gempita in Malaysia	14
Figure 2.3	Trend demand for magnesium materials in the world market	15
Figure 2.4	Types of common facing and core materials in sandwich panel	18
Figure 2.5	The layer configuration considerations in sandwich panel	23
Figure 2.6	Basic fatigue considerations in the application	26
Figure 2.7	System view in constant amplitude (CAL) waveform	27
Figure 2.8	Example fatigue limit for Aluminium and Steel on S-N curve	29
Figure 2.9	Crack Growth Curve	31
Figure 2.10	Three different types of crack opening	34
Figure 2.11	Trend of crack length, a , responded to number of cycles, N ; a) SMSP, b) SAMSP	36
Figure 2.12	Trend of crack length, a , responded to number of cycles, N for HSLA with different load ratio, R	37
Figure 2.13	AZ31B Mg alloy compact tension (CT) specimens of extrusion direction with three distinct orientations	38
Figure 2.14	Increasing load ratio on crack growth rate curves da/dN versus ΔK for 3 different directions CT specimens: a) L-T, b) T-L, c) T-R	38
Figure 3.1	Flow process for crack growth responded on sandwich metal panel	46
Figure 3.2	Fatigue and tensile: a) Dimension specimen specification (mm); and b) Sample of specimen	51
Figure 3.3	Solid materials and SMP: a) Dimension specimen specification (mm); and b) Sample of specimen crack growth	51
Figure 3.4	Performing of tensile test sample: a) Universal Testing Machine Instron 5569A (UTM); b) Strain estimated by an extensometer	53
Figure 3.5	Examine HSS and AZ31B fatigue behaviour using 100 kN of servo-hydraulic testing machine Instron 8801	55
Figure 3.6	Process of fatigue experiment	56
Figure 3.7	Initial step formation of sandwich metal development at each layer: a) Top layer (HSS); b) Centre layer (AZ31B); c) Bottom layer (HSS)	58

Figure 3.8	Final step formation of layer in sandwich metal panel development preparation with total thickness. $t = 10$ mm	58
Figure 3.9	Servo Hydraulic Machine for Crack Growth Test Placement	60
Figure 3.10	Preparation of three-dimensional (3D) model on sample static and compact tension specimen in rending simulation analysis	63
Figure 3.11	Creation of factorial design in Minitab 19	67
Figure 3.12	Creation of number of replicates in factorial design	67
Figure 4.1	The overall process of analysis study findings	69
Figure 4.2	Specimen for HSS; a) Stress-strain Curve, b) after fracture	72
Figure 4.3	Specimen for AZ31B; a) Stress-strain Curve, b) after fracture	72
Figure 4.4	Sample of fatigue testing specimen HSS and AZ31B at maximum range of yield strength a) before test, b) after test	75
Figure 4.5	Sample of fatigue testing specimen HSS and AZ31B at minimum range of yield strength a) before test, b) after test	75
Figure 4.6	Trend S-N curve diagram on experiment fatigue HSS	77
Figure 4.7	Trend S-N curve diagram on experiment fatigue AZ31B	79
Figure 4.8	Load needed for next crack growth behaviour test on sandwich metal development at 90% yield strength of HSS	80
Figure 4.9	Trend of crack length, a responded to Number of cycles, N_f for HSS at $f = 10$ Hz and $R = 0.1$	84
Figure 4.10	Trend of da/dN , (mm/N) responded to stress intensity, ΔK (MPa \sqrt{m}) for HSS at $f = 10$ Hz and $R = 0.1$	84
Figure 4.11	Trend of crack length, a responded to Number of cycles, N_f for AZ31B at $f = 10$ Hz and $R = 0.1$	87
Figure 4.12	Trend of da/dN , (mm/N) responded to stress intensity, ΔK (MPa \sqrt{m}) for AZ31B at $f = 10$ Hz and $R = 0.1$	87
Figure 4.13	Trend of crack length, a (mm) responded to Number of cycles, N_f for SMP at $f = 10$ Hz and $R = 0.1$	90
Figure 4.14	Trend of crack growth rate da/dN , (mm/N) responded to stress intensity, ΔK (MPa \sqrt{m}) for SMP at $f = 10$ Hz and $R = 0.1$	90
Figure 4.15	Stress-strain line from simulation for specimens HSS and AZ31B	92
Figure 4.16	Sample after tensile test simulation; a) HSS, b) AZ31B	92
Figure 4.17	Comparison stress-strain graph of σ_{ys} experiment and simulation for specimens HSS	93
Figure 4.18	Comparison stress-strain graph of σ_{ys} experiment and simulation for specimens AZ31B	93
Figure 4.19	Correlation of the experiment and simulation at yield values for HSS	94

Figure 4.20	Correlation of the experiment and simulation at yield values for AZ31B	94
Figure 4.21	Energy absorption for 3 different specimens corresponded to the total deformation with the same loaded and thickness	96
Figure 4.22	Improvement number of life cycle for 3 different specimens at $t = 10\text{mm}$, $R = 0.1$ and $f = 10\text{ Hz}$	98
Figure 4.23	Energy absorption for 3 different specimens at $t = 10\text{ mm}$ and $P = 90\%$ YS of HSS	99
Figure 4.24	Trend of 12 crack growth test on crack length, a (mm) response to the number of cycles, N_f for SMP at various factors	101
Figure 4.25	Trend of crack growth rate, da/dN (mm/N) responded to stress intensity factor range, ΔK (MPa $\sqrt{\text{m}}$) for SMP in different stress ratio, R and frequency, f ; a) $f = 10\text{Hz}$ and $R = 0.1$, b) $f = 10\text{Hz}$ and $R = 0.5$, c) $f = 5\text{Hz}$ and $R = 0.1$, d) $f = 5\text{Hz}$ and $R = 0.5$	102
Figure 4.26	The normal plot magnitude and direction of the number of cycles effect using $\alpha = 0.05$	103
Figure 4.27	Probability plot for number of cycles	104
Figure 4.28	Changes in number of life cycles toward factors frequency, f and stress ratio, R ; a) contour plot and b) surface plot	105
Figure 4.29	Correlation Number of Cycle between Empirical and Experimental response	106
Figure 4.30	Optimum values in maximising the number of cycles for sandwich metal panels	108
Figure 4.31	The normal plot toward crack length, effect using $\alpha = 0.05$	109
Figure 4.32	Probability plot for crack length	109
Figure 4.33	Changes in crack length with frequency, f and stress ratio, R : a) contour plot; and b) surface plot	110
Figure 4.34	Correlation of Crack Length Value between Empirical and Experimental response	111
Figure 4.35	Optimum values in maximising the value of crack length for sandwich metal panels	113
Figure 4.36	Pattern of 3 crack growth specimen validation for SMP using selected optimal parameter	114
Figure 4.37	Trend of crack growth analysis on SMP specimen 3 at selected optimal values	116
Figure 4.38	Comparison of the number of life cycles and crack length between solid material SMP at optimum parameter	117

LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
AZ31B	Magnesium Alloy
CAL	Constant Amplitude Loading
CT	Compact Tension
CG	Crack Growth
DOE	Design of Experiment
FEA	Finite Element Analysis
HCF	High Cycle Fatigue
HSS	High Strength Steel
LAV	Light Armour Vehicle
LCF	Low Cycle Fatigue
LHDCC	Lightweight High Ductility Cement Composite
MinDef	Ministry of Defence Malaysia
RHA	Rolled Homogeneous Armour
SMP	Sandwich Metal Panel
SMSP	Sandwich of Mild Steel Panel
SAMSP	Sandwich of Aluminium with Mild Steel Panel
UTS	Ultimate Tensile Strength
UHPC	Ultra-High-Performance-Concrete
UPNM	Universiti Pertahanan Nasional Malaysia
VMS	Von Mises Stress
YS	Yield Strength

LIST OF SYMBOLS

a	Crack Length
C	Material Constant (y-axis intercept)
da/dN	crack growth rate
E	Modulus of elasticity
ε	Strain
f	Frequency
Hz	Hertz
ΔK	Stress Intensity
ΔK_{th}	crack growth threshold
kN	Kilonewtons
ΔL	Change Length
L_0	Initial Length
L	Final Length
m	Material Constant (gradient of slope)
mm	Millimeter
Mpa	Megapascal
N	Newton
N	Total Number of Cycles
N_f	Number of Cycles to Failure
P	Applied Load
%	Per cent sign
R	Stress Ratio
W	Width
t	Thickness
σ_{max}	Maximum Stress Value
σ_{min}	Minimum Stress Value
$\Delta\sigma$	Cyclic Stress Range
$\Delta\sigma_a$	Cyclic Stress Amplitude
σ_m	Mean Stress
σ_{UTS}	Ultimate Tensile Strength
σ_{YS}	Yield Stress

CHAPTER 1

INTRODUCTION

1.1 Background Research

The application of crack growth on sandwich metal panel (SMP) is gaining attention in the field of the military, especially in the construction of light armoured vehicles (LAV). During service, the technical components that make up a movement mechanism are often exposed to cyclic or variable stress. Relevant examples often relate to the area of automotive research, such as military operation vehicles, which are an example of fatigue-prone constructions [1]. The development of light armoured vehicles (LAV) poses the possibility that the country will be able to carry out military operations in a more efficient and less risky way, especially when shot by high-velocity ammunition bullet, which will reduce its operability performance [2]. When metal and composite are exposed to a specific number of cyclic loadings, most fatigue failures in engineering structures are caused by exposure to fluctuate loading. To maintain the components' safety and integrity, a thorough knowledge of material behaviour is required. The amount of stress or strain cycles that a material can take before failing is often referred to as fatigue life [3, 4]. The number of loading cycles before the fracture forms may be used to estimate a component's service life [5].

The railway axles in Europe collapsed during operation in the mid-nineteenth century, prompting this important research of fatigue failure. Fairbairn in the United Kingdom and Wöhler in Germany performed laboratory tests in the early 1860s and reported their findings as graphs of applied stress, S , against the number of cycles to failure, N in their work [6]. Similar (S-N) curves have been utilised to design components and structures for metal and composite to prevent fatigue failures as a result of their research. Geometric models [7], microstructure and grain sizes [8, 9], surface finish through modelling works [10], loading conditions related to both constant and variable amplitude [11, 12], the environment through corrosion [13], and temperature [14, 15] are just a few of the factors that affect the fatigue life of engineering components. The fatigue damage may even further reduce the structural resistance with the presence of different kinds of imperfections, leading to increased local stresses and accelerated crack initiation and propagation. Crack growth (CG) is an important parameter that needs to be considered.

It is generally acknowledged that fatigue and crack growth must be taken into account in the design and failure analysis. The crack path must be determined as part of the full solution to the fatigue and crack growth issue [16]. The variables that govern the path followed by fatigue and crack growth are not entirely understood. Crack growth is a basic fracture mechanics concept that includes crack surface displacement, which is calculated using the trend number of fractures, a , and the number of cycles, N . The crack surfaces move relative to one another when stress is applied to a cracked body, and there are three modes of crack surface displacement [17, 18]. These include: Mode I , in which opposing crack surfaces move straight

apart; Mode *II*, in which crack surfaces move perpendicular to the crack front; and Mode *III*, in which crack surfaces move parallel to the crack front [18].

Moving forward with technology, new lightweight material should be introduced in sandwich metal panel development to observe the crack growth behaviour [19]. Given that metal structures are often exposed to fatigue stress, it is necessary to analyse the crack growth behaviour of sandwiched metal panels. Typically, a sandwich metal panel has more than two layers: a low-density core and a thin skin layer connected to either side. Sandwich metal panels are utilised in applications that need a high degree of structural strength while being lightweight [20]. Many researchers in the past focused on areas associated with the sandwich metal panels due to their relatively poor resistance impacting loading application [21, 22]. However, not many researchers studied crack growth behaviour on a sandwich metal panel. Admittedly, the sandwich metal panel can reduce the weight of material without compromising its application. The advantage of the sandwich metal panel in crack growth application is that delamination always occurs at the top layer during rugged movements or fluctuating loads [23].

1.1.1 Application of Sandwich Metal Panel

A sandwich metal panel (SMP) is a kind of laminated material that is unique. The high stiffness- and strength-to-weight ratios are the primary advantages of this lay-up. Integrated functions such as thermal insulation, buoyancy, and, in certain instances, strong acoustic insulation, high energy absorption capabilities, and integrated production are its additional benefits [24]. In an SMP, the faces will work together to create an effective stress pair counteracting the external bending moment, according to Zenkert D. [25]. The core protects the faces from buckling and wrinkling by resisting shear. The connection between the faces and the core, particularly in aviation applications, must be strong enough to withstand the shear and tensile pressures created between them.

The aviation industry is becoming more interested in the SMP idea and structures, which have been used in a wide range of applications. Cabin flooring in civil aircraft [26], control surfaces, landing bay doors [27], helicopter rotor blades and fuselages [28], satellite antennas, and solar panels are all examples of aeronautical applications. Moreover, the SMP idea has become one of the main construction methods for small and medium-sized ships in the boat building business [31]. SMP architecture is currently used for the primary structure of even bigger lightweight passenger ferries with built-in metal to reduce weight at the higher levels and increase the ship's seaworthiness [32]. SMP has emerged as a promising design idea for railway and subway cars, allowing for greater stiffness and, as a result, higher vibration eigenfrequencies [33]. Since they provide integrated thermal insulation in

the load-carrying structure, truck tankers for liquid fuels, milk, juice, and other substances also have a built-in SMP design [34].

1.1.2 Potential of Core in Sandwich Metal Development

These types of core designs are used due to their properties of lightweight, good impact resistance, and good energy absorption [35]. However, there are still limited studies on metal-based sandwich metal panels. There is a type of sandwich metal panel that uses a solid plate as their main core for the sandwich metal panel. For core material, the use of aluminium alloy prevails in various engineering fields [36]. However, J. Song et al. [37] reported that magnesium alloy has emerged as one of the materials with the potential of replacing aluminium alloy, thus becoming an alternative material for a core material in sandwich metal panels. Magnesium alloy has similar properties with that of aluminium alloys, such as formability and mass, making it a potential candidate for use in large-sized manufacturing industries, such as railway construction and military protection vehicle production [37]. However, there are some limitations on its core design, such as small adhesive areas and hollow design, both of which may affect the delamination and cracking rate. On top of that, lower core density may weaken the structural integrity of the sandwich metal panel. Therefore, for heavy applications such as light armoured vehicles, it is necessary to propose a core design that not only can sustain the high velocity impact but have a better rate of delamination under high compression or tension force.

1.2 Problem Statement

Special solid material for applications in the maritime, aviation, and automotive sectors are the most essential element of any product in the modern age. The presence and development of cracks produced by fatigue failure and crack propagation under repeated loading are a concern in most solid material constructions [4,10]. Due to its great material strength, the light armoured vehicle (LAV) plays a major part in the protective action [38]. The introduction of new materials and advancements to existing materials used to build LAV has resulted in improved protection and a decrease in the LAV's weight throughout history [2, 39]. However, it should be noted that the significant weakness of LAV is due to high impact of ammunition bullets with high velocity until the crack starts to form under fluctuating movements, which will reduce its life durability performance and operability.

As a result, a new lightweight sandwich metal panel development should be developed to replace the current solid material utilised in LAV. Because LAV is often exposed to cyclic stress conditions, a crack growth behaviour study for sandwiched metal panels is required, particularly on its performances in terms of constant amplitude loading. The appropriate material involving lightweight material concerning the crack growth behaviour needs to be established. The use of magnesium alloy materials is important as it has several advantages in lightness and shock absorption properties [40]. As a sandwich metal panel, its weight may pose an issue, especially in terms of maneuverability in the war zone and rescue operations. However, the existing solid material in LAV has shortcomings in terms of strain and energy absorption for crack growth behaviour application. These shortcomings need