

BALLISTIC IMPACT PERFORMANCE OF WET LAMINATION
KEGA

by

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TABLE OF CONTENTS

ACKNOWLEDGMENT	ii
TABLE OF CONTENTS	iii
LIST OF TABLES	viii
LIST OF FIGURES	x
LIST OF ABBREVIATIONS	xiii
LIST OF SYMBOLS	xv
ABSTRAK	xviii
ABSTRACT	xx
CHAPTER 1: INTRODUCTION	1
1.1 Fiber Metal Laminate at a Glance	1
1.2 Basic Armor Requirement	3
1.3 Problem Statement	4
1.4 Research Objective	6
1.5 Scope of Study	7
1.6 Significance of Study	8
1.7 Contribution of the Study	9
1.7.1 Methodology Contribution	9
1.7.2 Practical Contribution	10
1.8 Structure of the thesis	10
CHAPTER 2: LITERATURE REVIEW	13
2.1 Introduction	13

2.2	Ballistic Science Application in Fiber Metal Laminate (FML)	14
2.3	The Absorption Energy Mechanism in Metal Fiber Laminate (FML)	17
2.3.1	Contributing Factors in Metal Layer	17
2.3.2	Contributing Factors Fiber Layer	19
2.3.3	Contributing Factors in Matrix	21
2.4	Hard Body Armor- Development and Application	24
2.4.1	Hard Body Armor at a Glance	25
2.4.2	Modern Hard Body Armor	26
2.4.3	Fundamentals of Ceramic Hard Body Armor	29
2.4.4	Defeating Framework in Ceramic - Hard Body Armor	33
2.5	Design Parameters Influencing the Ballistic Performance	35
2.5.1	Effect of Projectile and Target Plate Hardness on the Kinetic Energy Density	36
2.5.2	Effect of Projectile Geometry and Target Plate Thickness	37
2.5.3	Effect of Projectile Mass and Target Plate Density	37
2.5.4	Effect of Projectile Velocity and Target Material Configuration	40
2.6	Ballistic Science Phase Development: Analysis Approaches	42
2.7	Analytical Model Analysis	44
2.7.1	Modified Classical Laminate Theory	45
2.7.2	First Ply Failure Analysis	51
2.7.3	Lamina Failure Criterion	53
2.7.4	Wen's Model: Ballistic Impact Performance Analysis	57
2.7.4.1	Wen's Model: Depth of Perforation (P) Wen $P \leq L_n$	60
2.7.4.2	Wen's Model: Perforation Energy (E_k) Analysis	63

2.7.4.3 Wen's Model: Ballistic Limit Performance (V_{50}) Analysis	64
2.8 Ballistic Testing Technique	65
2.8.1 The Live Firing Experiments for Ballistic Test	65
2.8.2 National Institute of Justice-(NIJ) Standards	66
2.9 Summary	69
CHAPTER 3: RESEARCH METHODOLOGY: ANALYTICAL MODEL	71
3.1 Introduction	71
3.2 Analytical Model: Prediction for Ballistic Impact Performance	73
3.3 Summary	76
CHAPTER 4: RESEARCH METHODOLOGY: EXPERIMENTAL TEST	77
4.1 Introduction	77
4.2 Specimen Fabrication for Mechanical Tests: Basic Lamina Properties	80
4.2.1 Tensile Test for Fabric Constituent	81
4.2.2 Compression Test for Fabric Constituent	82
4.2.3 In-Plane Shear Test for Fabric Constituent	83
4.2.4 Tensile Test for Aluminum Alloy Sheet	84
4.3 Specimen Fabrication for Mechanical Tests: Static Linear Compression Limit	85
4.3.1 Through Thickness Compression Strength Test	87
4.3.2 Gas Gun Ballistic Impact Test	88
4.4 Summary	92

CHAPTER 5: RESULTS AND DISCUSSION	93
5.1 Introduction	93
5.2 The Basic Lamina Properties: Engineering Properties and Strength Parameters	94
5.3 Prediction of Stress-Strain in Fiber Metal Laminate (FML) by Modified Classical Laminate Theory (MCLT) Under In-Plane Tensile Load	95
5.3.1 Part Configuration Designs: Safety Index Value	97
5.3.2 Predicted Safety Index Performance for KeGa Configuration Designs	98
5.4 Quasi Static Linear Elastic Limit (σ_e) Performance	104
5.5 Prediction of Ballistic Limit Performance (V_{50})	109
5.5.1 Effect of Ballistic Impact Performance (V_{50}) Based on 5 Percent Reduction of Main Parameters	112
5.5.2 Prediction of Perforation Energy (E_k)	115
5.5.3 Depth of Perforation	118
5.6 Gas Gun Ballistic Impact Test	121
5.6.1 Ballistic Limit Performance (V_{50})	122
5.6.2 Depth of Perforation	125
5.6.3 Perforation Energy	127
5.7 Damage Mode Mechanism	129
5.7.1 Front Face Damage Mechanism	130
5.7.2 Rear Face Damage	135
5.8 Summary	136

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS	138
6.1 Conclusion	138
6.2 Recommendation for Future Studies	140
REFERENCES	141
APPENDICES	

LIST OF TABLES

	Page
Table 2.1: Material properties in FML for hard plate armor	24
Table 2.2: Technical aspects of SAPI and ESAPI (source BAE Systems)	28
Table 2.3: Parameters affecting the ballistic resistance proficiency	35
Table 2.4: List of analytical model with target density parameter	39
Table 2.5: NIJ standard ballistic limit performance	68
Table 2.6: NIJ standard perforation and backface signature	69
Table 3.1: Laminate orientation code for proposed configuration design	74
Table 4.1: List of fabric constituent material for mechanical tests	80
Table 4.2: List of metal constituent for mechanical tests	80
Table 4.3: Distribution of the specimen for designated experiment	81
Table 4.4: The configuration design of specimen	86
Table 4.5: Description of the test parameters	90
Table 4.6: Target panel descriptions	90
Table 5.1: Elastic engineering properties	94
Table 5.2: Basic strength parameters of metal constituent	94
Table 5.3: Basic strength parameters of fabric constituent	95
Table 5.4: The mechanical properties of constituents of GLARE 2-2/1	95
Table 5.5: The mechanical properties of metal constituents of GLARE 2-2/1 at plastic segment	96
Table 5.6: Predicted safety index of various FML design	98
Table 5.7: Design parameters for performance analysis	99

Table 5.8:	Result of the through thickness compression performance parameters	105
Table 5.9:	Ballistic limit performance (V_{50}) of all panels	110
Table 5.10:	Prediction ballistic impact performance (V_{50}) after 5% reduction of selected parametric input for the configuration design E	114
Table 5.11:	Hierarchy of the selected parametric input on the V_{50} performance	114
Table 5.12:	Perforation Energy for all configuration designs	116
Table 5.13:	Hierarchy of the parametric input for perforation energy performance	118
Table 5.14:	Depth of perforation for KeGa configuration design	120
Table 5.15:	Ballistic impact test results of selected KeGa configuration design for hemispherical head projectile	121
Table 5.16:	Ballistic impact test results of selected KeGa configuration design for conical head projectile	122
Table 5.17:	Ballistic impact test results of selected KeGa configuration design for the flat ended head projectile	122
Table 5.18:	Depth perforation of selected KeGa configuration design	125
Table 5.19:	Predicted depth of perforation	125
Table 5.20:	Perforation energy result: Ballistic impact test and Wen's model	127

LIST OF FIGURES

	Page
Figure 1.1: Fiber metal laminates	2
Figure 2.1: Schematic of a typical configuration of FML	15
Figure 2.2: Shapes and designs of contemporary hard plate armor	27
Figure 2.3: Three components armor system	31
Figure 2.4: Three component system	32
Figure 2.5: Defeating framework in ceramic	34
Figure 2.6: Bi -linear stress-strain curve of metal	51
Figure 2.7: The schematic diagram of projectile geometrical shape	59
Figure 2.8: The schematic diagram of conical nose perforating on semi infinite target plane $P \leq L_n$	61
Figure 2.9: Schematic diagram of flat-ended impacting on semi-infinite plate $P > L$	63
Figure 2.10: Firing devices based on pistol or rifle gun system	66
Figure 2.11: Gas gun equipment	66
Figure 3.1: Research methodology for analytical model	72
Figure 3.2: Ballistic Impact Performance Assessment Approach	75
Figure 4.1: Research methodology for mechanical test	78
Figure 4.2: Research methodology for ballistic impact test	79
Figure 4.3: Experimental set up and sample for specimen for the ASTM 3039M-00	82
Figure 4.4: Special jig for ASTM 3410M-03 and sample of specimen	83
Figure 4.5: Specimen for the ATM D3518M-94(2001)	84
Figure 4.6: Aluminum sample for ASTM E8M-15a	85
Figure 4.7: Basic stacking sequence of configuration A	87

Figure 4.8:	Schematic of the gas gun system	89
Figure 4.9:	Digital Caliper	91
Figure 5.1:	Stress-strain curve of GLARE 2-2/I under in-plane tensile Loading	97
Figure 5.2:	Safety Index Performance	101
Figure 5.3:	Configuration design resistance load performance	102
Figure 5.4:	Comparison of the quasi static elastic limit performance	105
Figure 5.5:	The stretching and thinning mode of failures of the aluminum layer	106
Figure 5.6:	The horizontal and vertical splitting of the specimen	107
Figure 5.7:	The development of the delamination process	107
Figure 5.8:	Stress-strain curve of configuration D and E under through Thickness compression	108
Figure 5.9:	Bullet Geometrical Shape for Design E	112
Figure 5.10:	Configuration design E comparison in V_{50} performance	113
Figure 5.11:	Perforation energy (E_k) performance for configuration design E	116
Figure 5.12:	Configuration design E comparison in energy performance	117
Figure 5.13:	Ballistic impact performance line chart: A. Ballistic impact test B. Wen's model	124
Figure 5.14:	Predicted and ballistic impact test: perforation energy data for hemispherical projectile shape	128
Figure 5.15:	Front damage of FML-KeGa plate: Configuration design C	130
Figure 5.16:	Oval shape pattern of KeGa: Configuration design F	131
Figure 5.17:	High speed camera footage : Projectile in yaw movement	131
Figure 5.18:	Aluminum layer with stretching and plugging mode of failure	132
Figure 5.19:	Projectile head before impact	133
Figure 5.20:	Development of internal damage mode	133

Figure 5.21: Formation debris due to the fiber and matrix fracture	133
Figure 5.22: Damage mode in the composite layer: Matrix cracking and fiber fracture	134
Figure 5.23: Damage mode mechanism due to hemispherical and conical head	134
Figure 5.24: Debonding formation	135
Figure 5.25: Petaling formation	136
Figure 5.26: Bulging formation	136

LIST OF ABBREVIATIONS

AP	Armor Piercing
APM	Armor Piercing Material
ARALL	Aramid Fiber Reinforced Aluminum Laminate
BAE	British Aerospace Engineering
CARALL	Carbon Fiber Reinforced Aluminum Laminate
CF/PEEK	Carbon Fiber Reinforced Poly-ether-ether
CFRP	Carbon Fiber Reinforced Plastic
CLT	Classical Laminate Theory
CMC	Ceramic Matrix Composite
CPEI	Carbon Fiber Reinforced Poly-Ether-Imide
DUT	Delf University of Technology
ESAPI	Enhanced Small Arms Protective Insert
FDM	Finite Difference Method
FEA	Finite Element Analysis
FEM	Finite Element Method
FML	Fiber Metal Laminate
FRP	Fiber Reinforced Plastic
FSP	Fragment Simulating Projectile
GFPP	Glass Fiber Reinforced Polypropylene
GFRP	Glass Fiber Reinforced Polypropylene
GLARE	Glass Laminated Reinforced Epoxy
GPEI	Glass Fiber Reinforced Poly-ether-Imide
HV	Hardness Vickers

HOSDB	Home Office Scientific Development Branch
HRC	Hardness Rockwell C
HULD	Hardened Unit Load Device
KE	Kinetic Energy
KeGa	Kevlar Glass Aluminum
LPS	Lyohkaya Pulya Serdtse
MCLT	Modified Classical Laminate Theory
NATO	North Atlantic Treaty Organization
NIJ	National Institute of Justice
NIST	National Institute of Standards and Technology
OLEs	Office of Law Enforcement Standards
OTV	Outer Tactical Vase
PP/PP	Polypropylene Fiber Reinforced Polypropylene Composite
RHA	Rolled Homogeneous Armor
SAPI	Small Arm Protective Insert
UHMWP	Ultra-High Molecular Weight Polyethylene
VPN	Vickers Pyramid Number
WC	World Carbide

LIST OF SYMBOLS

SYMBOL	DESCRIPTION	UNIT
σ_e	Quasi static elastic limit	MPa
V_{50}	Ballistic limit performance	m/s
V_{ini}	Initial impact velocity	m/s
σ_{ij}	Stress components in tensor notation	MPa
σ_n	Mean resistive pressure	MPa
σ_s	Cohesive static resistive pressure	MPa
σ_d	Dynamic resistive pressure	MPa
β	Empirical constant of projectile nose geometry	-
ρ_t	Laminate plate density	kg/m ³
ρ_{pr}	Projectile density	kg/m ³
A	Cross sectional area of projectile	m ²
m	Mass of projectile	kg
P	Depth of penetration	mm
D	Diameter of the projectile	mm
a	Projectile radius	mm
E_{ke}	Kinetic energy of projectile	J
E_k	Perforation energy	J
E_m	Mass efficiency factor	-

E_t	Thickness efficiency factor	-
T	Thickness of the laminate	m
t	Material thickness	mm
L	Projectile length shank	mm
L_n	Projectile nose length	mm
Ψ	Calibre head radius	mm
ε_{ij}	Strain components in tensor notation	-
ε_{xy}^0	The reference plane strain	-
γ_6	Shear strain	-
τ_6	Shear stress	MPa
κ_{xy}	Curvatures	1/m
z	Distance of lamina from the midplane	-
Q_{ij}	Reduced stiffness matrix	GPa
Q_{xys}	Transformed reduced stiffness matrix	GPa
N_{xy}	Normal force per unit length	N/m
N_s	Shear force per unit length	N/m
M_{xy}	Bending moments per unit length	N-m/m
A_{ij}	Extensional stiffness	MN/m
B_{ij}	Coupling stiffness	kN
D_{ij}	Bending stiffness	N-m
$[a]$	Laminate compliance matrix	m/N

$[b]$	Laminate compliance matrix	1/N
$[c]$	Laminate compliance matrix	1/N
$[d]$	Laminate compliance matrix	1/N-m
E_{plstc}	Young's modulus at plastic region	GPa
$E_{elastic}$	Young's modulus at elastic region	GPa
σ_{ult}	Ultimate tensile strength	MPa
σ_{yld}	Yield strength	MPa
E_1	Young's modulus at longitudinal tension	GPa
E_2	Young's modulus at transverse tension	GPa
G_{12}	In plane shear modulus	GPa
ν_{12}	In plane major Poisson's ratio	-
ν_{21}	Minor Poisson's ratio	-
$f_{1,2,6}$	Strength tensor coefficient	1/MPa
F_{1t}	Longitudinal tensile strength	MPa
F_{2t}	Transverse tensile strength	MPa
F_{1c}	Longitudinal compressive strength	MPa
F_{2c}	Transverse compressive strength	MPa
F_6	In plane shear strength	MPa
$f(\alpha_f)$	Safety condition for FRP layer	-
$f(\alpha_m)$	Safety condition for metal layer	-

PRESTASI HENTAMAN BALISTIK KE ATAS LAPISAN BASAH KEGA

ABSTRAK

Keperluan kepada mod pergerakan efektif, kos yang berdaya saing, perlindungan yang boleh dipercayai dan ringan telah menjadi keutamaan kepada industri perisai perlindungan dalam fasa pembangunan reka bentuk produknya seperti panel perisai badan keras. Akibatnya, pembangunan yang pesat dalam bahan perisai baru, ditambah dengan kepesatan kemajuan teknologi telah merangsang pertumbuhan dalam industri ini. Bagi menyokong kepentingan industri perisai perlindungan untuk pencarian bahan-bahan baru terutamanya didalam segmen perisai perlindungan badan keras, penyelidikan semasa telah mengambil inisiatif untuk menyiasat kesan prestasi hentaman balistik terhadap bahan daripada variasi baru lamina logam serat (FML) yang berdasarkan kepada Kevlar 29, S-Glass dan aluminium aloi 2024 T3 yang dikenali sebagai KeGa. Oleh itu, salah satu isu yang menarik perhatian kajian semasa adalah FML-KeGa lamina yang baru ini perlu mempunyai kaedah penilaian yang munasabah untuk mewajarkan keupayaan prestasinya. Berkaitan dengan isu ini, penyelidikan ini telah menggunakan dua pendekatan iaitu analitikal dan eksperimen sebagai kaedah penilaian. Pendekatan analisis berdasarkan macromechanics dan kuasa gelombang analisis setempat digunakan untuk meramal indeks keselamatan sebagai status keupayaan dan prestasi hentaman balistik lamina KeGa. Bagi segmen eksperimen, ujian mekanikal telah digunakan untuk menentukan asas kekuatan parameter lamina dan kuasi-statik had elastik linear. Seterusnya, ujian kesan impak tembakan daripada senjata yang pelancarnya digerakkan oleh kuasa gas telah digunakan untuk mengukur prestasi hentaman balistik lamina KeGa. Hasil kajian menunjukkan bahawa ramalan hentaman prestasi balistik KeGa lamina adalah

sepadan dengan keputusan kajian eksperimen. Tambahan pula, keputusan ini juga menunjukkan bahawa saiz geometri peluru sebagai parameter utama untuk memasuki mod penembusan yang berkesan manakala ketebalan plat adalah signifikan bagi menambahbaik keupayaan rintangan plat. Secara ringkas, kaedah penilaian dalam kajian ini menyediakan platform permulaan bagi tujuan penyelidikan serta pembangunan untuk KeGa dan logam serat lamina.

BALLISTIC IMPACT PERFORMANCE OF WET LAMINATION KEGA

ABSTRACT

The requirement for effective mobility mode, cost efficient, reliable protection and lightweight has become the main priority to the armor industries in their product design development phases such as hard body armor panel. As a result, rapid development in the new armor materials, coupled with more technological advancements has fueled growth in the industry. To support the interest of the armor industries for new materials particularly in hard body armor segment, the current research has taken an initiative to investigate the ballistic impact performance of a new variant of fiber metal laminate (FML) which consists of Kevlar 29, S-glass fibers and aluminum alloy 2024 T3 known as KeGa. As such, one of the issues that have caught the attention of the current study is that a newly FML-KeGa laminate must have reliable evaluation methods in order to justify its performance capability. In relation to this issue, the current research has employed both analytical and experimental approach as the evaluation method. The analytical approach based on macromechanics and wave dominated localized analysis were used to predict the safety index as fitness status and the ballistic impact performance of the KeGa laminate. For the experimental segment, the mechanical tests were employed to determine the basic lamina strength parameters and quasi-static linear elastic limit. After that, the gas gun impact tests were employed in order to quantify the ballistic impact performance of the KeGa laminate. Results showed that predicted ballistic impact performance of KeGa laminate is in good agreement with the experimental results. Furthermore, the results also signified that the geometrical size of the projectile as the main parameter for effective perforation mode while the plate

thickness was significant for better plate resistance capability. In brief, the evaluation methods in this study provide a platform for research and development of KeGa and fiber metal laminate.

CHAPTER 1

INTRODUCTION

1.1 Fiber Metal Laminate at a Glance

The expanding application and demand towards new resources of material have spurred the research activities to develop and design a material with advanced characteristics. The features include the high resistance towards the environment, less maintenance while in service, excellent safety standard delivery, high damage tolerance properties, longer service life and reduced weight and cost. These are some of the key factors that affect the design of a new material. The need for material with the above characteristics has resulted in overwhelming findings for advanced material development. To date, the conventional monolithic materials have been expanded further from metals, ceramics and polymers into new generation of advanced materials. The new generations of advanced materials may include nanocomposite, metal-matrix composite and fiber metal laminate.

Fiber metal laminate (FML) is among new materials that has received positive response from the aerospace and aviation industry. It utilizes the concept of having the advantages and disadvantages from two different types of materials to form a hybrid structural material. Particularly, the fiber metal laminate application can be found on jumbo aircraft, such as the Airbus 380. To understand the basic formation

of the FM, the construction of fiber metal laminate is depicted schematically in Figure 1.1.

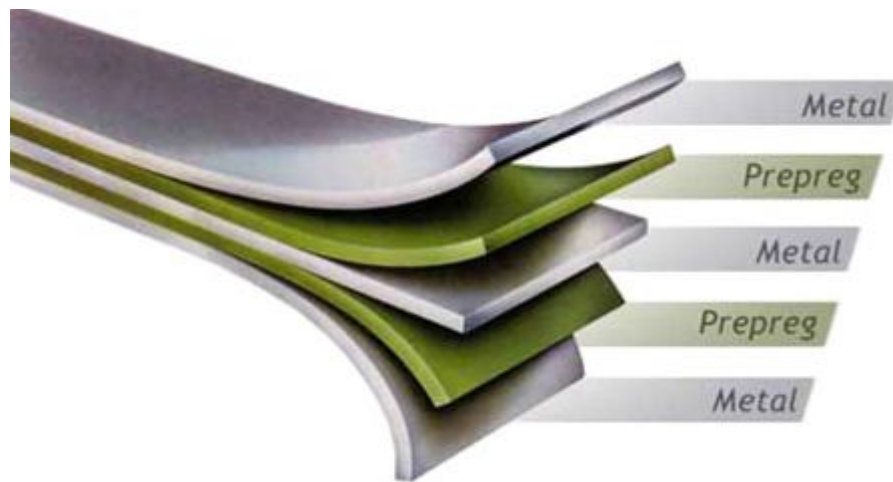


Figure 1.1: Fiber metal laminate. [Source: Soltani et al., (2011)]

Briefly, the fiber metal laminate (FML) consists of a combination of interleaved layers of high strength thin metal alloy and fiber reinforced polymer embedded into thermosetting or thermoplastic based matrix (Yeh et al., 2011; Moriniere et al., 2012; Tan & Hazizan, 2012; Abdullah et al., 2015). The achievement in this FML concept has inspired the research community over the years to develop an infinite variety of FML such as Glare, Arall, Care and etc. (Sun & Potti, 1993; Carillo & Cantwell, 2009; Santiago et al., 2013; Vasumathi & Murali, 2013; Wangqing et al., 2014). Other than this, the lamination method is also significant in the FML concept. Generally, lamination method can be categorized into the wet lamination or dry (prepreg) lamination method (Sultan et al., 2012; Chen et al., 2013). By definition, the wet lamination is a method of making a composite product by applying the resin system as a liquid when the constituent material is put in place. In contrast, the dry

(pre-preg) lamination is a method whereby the resin system is impregnated into the constituent material to make a composite product (Armstrong & Barret, 1998).

From the literature, a large amount of the fiber metal laminate (FML) works chose the dry lamination method over the wet lamination method. Nevertheless, there are some efforts looking into the potential of the wet lamination method in manufacturing the next generation of the FML due to the increasing cost in manufacturing the FML through the dry lamination method (Sinmazcelik et al., 2011; Ramadhan et al., 2012; Vasumathi & Murali, 2013).

1.2 Basic Armor Requirement

The law enforcement and military organizations require equipment with a design that is fast, more agile, reliable, cost efficient, possess improved protection criteria and effective mobility mode to support and strengthen the ground forces. These design requirements have known to be the present trend in the ballistic armor protection system (Montgomery et al., 1997; Zaera, 2011). According to these authors, the rapid transformations in the armor protection system are significantly related to the vast development in the anti-armor materials. As a result, an increased demand for a better lightweight armor protection system such as the hard body armor and lightweight vehicle armor led to the requirement of the new armor materials.

In conjunction to the above, the weight factor becomes the main driving force for developing the new armor materials. Obviously, the armor industry has introduced a variety of the armor materials such as aluminum, titanium, ceramics, ceramic matrix composites and armor grade composites. However, the conventional lightweight