BALLISTIC IMPACT PERFORMANCE OF WET LAMINATION KEGA

by

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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 pelindungan 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.

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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.

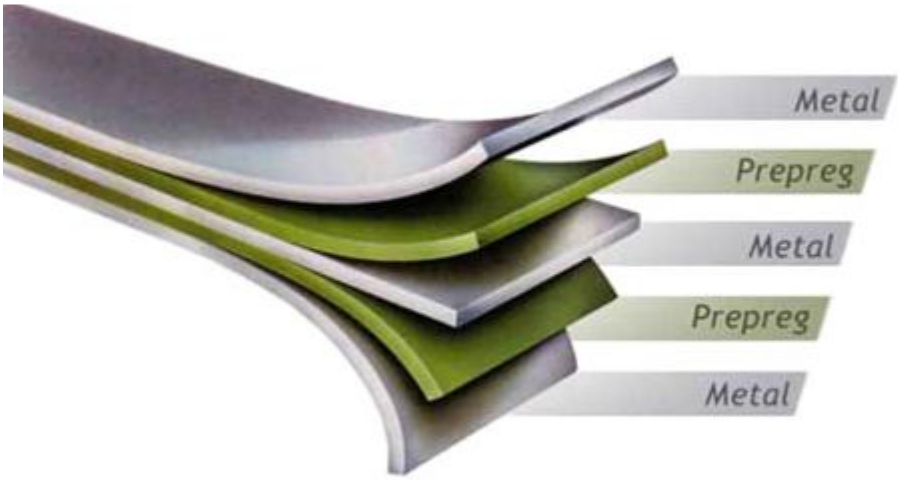

Figure 1.1: Fiber metal laminate. [Source: Soltani et al., (2011)]

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 (pre-preg) 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