

IMPACT STUDIES ON THERMOPLASTIC COMPOSITE ARMORS REINFORCED WITH 2D/3D FABRICS

BANDARU ASWANI KUMAR



**DEPARTMENT OF APPLIED MECHANICS
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by

BANDARU ASWANI KUMAR
Department of Applied Mechanics

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This thesis is dedicated to my family and friends

Certificate

This is to certify that the thesis entitled “**Impact Studies on Thermoplastic Composite Armors Reinforced with 2D/3D Fabrics**” being submitted by *Mr. Bandaru Aswani Kumar* to the **Indian Institute of Technology Delhi** for the award of the degree of **Doctor of Philosophy** in Applied Mechanics is a record of original, bonafide research work carried out by him under my supervision and guidance. The thesis work, in my opinion, has reached the requisite standard fulfilling the requirements for the degree of Doctor of Philosophy.

The results contained in this thesis have not been submitted in part or in full, to any other University or Institute for the award of any degree or diploma.

Date:

Place: New Delhi

Dr. Suhail Ahmad

Professor

Department of Applied Mechanics

Indian Institute of Technology Delhi

New Delhi-110016, India

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(Bandaru Aswani Kumar)

Abstract

The pursuit of mass-efficient materials and architecture for use in armor technologies has been the focus of many research projects in past years. Most of the researched armor materials are in the area of lightweight polymer composites. Previously, the material of choice was lightweight Aramid (Kevlar). New manufacturing technologies and techniques have enabled the production of armor (body/vehicle) using thermoplastic (TP) matrix with high performance reinforcements, which exhibit the highest strength to weight ratios. However, a major concern affecting the efficient use of TP armors is the lack of technology and data behind the production of the armors. The focus of this research is to assess the ability of the homogeneous and hybrid fiber reinforced TP polymer composite armors to withstand the impact of the NIJ-STD-0106.01 Type IIIA (9 mm full metal jacket projectile 426 ± 15 m/s), using the ballistic impact tests and hydrocode simulations.

Different types of fabrics are constructed during different phases of the manufacturing process. In Phase-1, homogeneous Kevlar fabrics are produced with an architecture of 2D plain woven (2D-P), 3D orthogonal (3D-O) and 3D angle interlock (3D-A). Based on the performance of the composite laminates manufactured with Phase-1 fabrics, homogeneous and hybrid fabrics with reduced areal density are woven in Phase-2. In Phase-2, homogeneous fabrics with Kevlar/basalt yarns and hybrid fabrics with the combination of Kevlar and basalt yarns are produced with 2D-P and 3D-A architectures. The fabrics produced are used as reinforcements to manufacture composite laminates and actual armor panels, with polypropylene (PP) as resin, using vacuum assisted compression molding method. Interfacial property between PP resin and Kevlar/basalt fabrics is improved by adding a coupling agent called, maleic anhydride grafted PP (MAg-PP) to PP. The homogeneous and hybrid TP composites reinforced with Kevlar/basalt fabrics yielded a 2.65% to 35.75% reduction in the density as compared to the conventional thermoset (TS) composites, indicating the achievement of weight reduction in case of presently developed TP composites.

The mechanical characterization of the 2D/3D TP composites is studied by performing static tensile and in-plane compression tests. The tensile modulus of TP composites is 4.73% to 64.08% higher than the tensile modulus of TS composites reported in the literature. Hybridization showed a significant improvement in the tensile and in-plane compression behavior of TP composites in terms of modulus, strength and failure strain. The material constants obtained from experimental characterization of new materials are used in the numerical simulations. Experimental findings of ballistic responses are validated, hence, established a reliable numerical model.

Experimental investigations are carried out to determine the influence of fabric architecture and hybridization on the low velocity impact (LVI) response of TP composite laminates. LVI tests are conducted using a drop-weight impact equipment at the energy level of 240 J. The LVI response of the TP composites is compared in terms of peak force, energy absorption and damage patterns. LVI resistance of homogeneous composites is increased from 2D to 3D composites (Phase-1), denoting the influence of fabric architecture. Hybridization also significantly improved the energy absorption capacity of the homogeneous 2D/3D composites (Phase-2) of lower areal density. Due to hybridization, the impact resistance of Kevlar composites with lower areal density is increased by 45% to 51% and 23% to 26%, in terms of peak force and energy absorption, respectively.

The ballistic impact tests are imparted with NIJ-STD-0106.01 Type IIIA threat level 9 mm full metal jacket (FMJ) on homogeneous and hybrid armor panels using standard test facilities, for an impact velocity range between 365 m/s to 438 m/s. Damage patterns, residual velocity and ballistic limit are measured from the experiments. The ballistic test results revealed that in the case of Kevlar homogeneous armor panels (Phase-1), for the similar areal density of the armors, 2D armor panels are more susceptible to impact induced damage than the 3D armors. Kevlar homogeneous composite armors with fabric architectures of 3D-O and 3D-A (Phase-1) are able to confront the 9 mm FMJ projectile, whereas, the 2D plain woven armors failed. Sixteen layer Kevlar 3D homogeneous armor panel exhibited zero deformation within the velocity range

defined by NIJ-STD-0106.01 Type IIIA (426 ± 15 m/s). In the case of hybrid armor panels (Phase-2), the symmetric armor panel is able to withstand 9 mm FMJ up to an impact velocity of 415 m/s while non-symmetric armor panel failed within the impact velocity of 365 m/s to 395 m/s. However, hybrid armor panel with a microcellular sheet (1.56 kg) exhibited zero deformation on the back face with a 15.67% reduction in the weight as compared to the sixteen layer Kevlar 3D homogeneous armor panel (1.86 kg).

Hydrocode simulations are carried out using ANSYS-AUTODYN v. 14.0, 14.5 to obtain an estimate for the ballistic limit velocity, residual velocity and failure modes. A material model is developed in hydrocode simulations by implementing the material constants obtained from experimental characterization, to validate the mechanical properties of the presently manufactured 2D/3D TP composites. Post-impact damage patterns obtained from the simulations are compared with the experimental results to assess the performance of the simulations. Good correlation between the hydrocode simulations and experimental results is observed, both in terms of failure modes and damage patterns with a percentage difference of 3.32% to 6.66% and 3.16% to 7.67% for Phase-1 and Phase-2 armors, respectively. The material model implemented is able to accurately predict the residual velocities and ballistic limit also. The ballistic limit predicted from simulations are in the range of 376 m/s to 470 m/s for Phase-1 armors and 307 m/s to 490 m/s for Phase-2 armors.

सार

बड़े पैमाने पर कुशल सामग्री और कवच प्रौद्योगिकियों में उपयोग के लिए वास्तुकला का पीछा पिछले कुछ वर्षों में कई अनुसंधान परियोजनाओं का ध्यान केंद्रित किया गया है। शोध किया कवच सामग्री के सबसे हल्के बहुलक कंपोजिट के क्षेत्र में हैं। इससे पहले, पसंद की सामग्री हल्के अरमिद (केवलर) था। नई विनिर्माण प्रौद्योगिकी और तकनीकों कवच (शरीर / वाहन) के उत्पादन के लिए सक्षम है उच्च प्रदर्शन के सुदृढीकरण, जो सर्वोच्च शक्ति के अनुपात में वजन करने के लिए प्रदर्शन के साथ थर्मोप्लास्टिक (टीपी) मैट्रिक्स का उपयोग कर। हालांकि, एक प्रमुख चिंता का विषय टी.पी. कवच के कुशल उपयोग को प्रभावित करने कवच के उत्पादन के पीछे प्रौद्योगिकी और डेटा की कमी है। इस शोध का ध्यान सजातीय और संकर फाइबर की क्षमता का आकलन करने के लिए है प्रबलित टी.पी. बहुलक मिश्रित कवच एनआईजे एसटीडी 0,106.01 प्रकार IIIA के प्रभाव का सामना करने के लिए (9 मिमी पूर्ण धातु जैकेट फेंकने के 426 ± 15 एम / एस) का उपयोग, बैलिस्टिक प्रभाव परीक्षण और हाइड्रोक्लॉड सिमुलेशन।

कपड़े के विभिन्न प्रकार के निर्माण की प्रक्रिया के विभिन्न चरणों के दौरान निर्माण कर रहे हैं। पहले चरण 1 में, सजातीय केवलर कपड़े 2 डी के एक वास्तुकला सादे बुना (2 डी पी), 3 डी ऑर्थोगोनल (3 डी ओ) और 3 डी कोण गूँथ (3 डी-ए) के साथ उत्पादन कर रहे हैं। चरण-1 कपड़े, कम अखाड़ा घनत्व के साथ सजातीय और संकर कपड़ों के साथ निर्मित समग्र लामिनेट्स के प्रदर्शन के आधार पर पहले चरण 2 में बुना जाता है। चरण-2 में, केवलर / बेसाल्ट यार्न और केवलर के संयोजन के साथ संकर कपड़े और यार्न बेसाल्ट के साथ सजातीय कपड़े 2 डी और 3 डी-P-ए आर्किटेक्चर के साथ उत्पादन कर रहे हैं। उत्पादित कपड़े सहायता वैक्यूम संपीड़न मोल्डिंग विधि का उपयोग कर, सुदृढीकरण पोलिप्रोपलीन (पीपी) राल के रूप में के साथ, समग्र लामिनेट्स और वास्तविक कवच पैनेलों का निर्माण करने के लिए के रूप में इस्तेमाल कर रहे हैं। पीपी राल और केवलर / बेसाल्ट कपड़े के बीच इंटरफेसियल संपत्ति नामक एक युग्मन एजेंट जोड़कर सुधार हुआ है, मेलिडक एनहाइड्राइड पीपी से पीपी (सदस्यता पीपी)। सजातीय और संकर टी.पी. कंपोजिट केवलर / बेसाल्ट

कपड़ों के साथ प्रबलित घनत्व में 2.65% 35.75% की कमी झुकेंगे पारंपरिक थर्मोसेट (टीएस) कंपोजिट की तुलना में, वर्तमान में विकसित टी.पी. कंपोजिट के मामले में वजन कम करने की उपलब्धि का संकेत है।

2 डी / 3 डी टीपी मिश्रित लामिनेट्स के यांत्रिक लक्षण वर्णन को स्थैतिक तन्यता और इन-प्लेन संपीड़न परीक्षणों द्वारा किया जाता है। साहित्य में टीएस कंपोजिट के तन्यता मापांक की तुलना में टीपी कंपोजिट का तन्य मापांक 4.73% से 64.08% अधिक है। माँड्यूलस, ताकत और विफलता तनाव के संदर्भ में संकरण में टी.पी. कंपोजिट के तन्यता और इन-प्लेन संपीड़न व्यवहार में एक महत्वपूर्ण सुधार दिखाई दिया। नई सामग्री के प्रयोगात्मक लक्षण वर्णन से प्राप्त सामग्री स्थिरांक संख्यात्मक सिमुलेशन में उपयोग किया जाता है। बैलिस्टिक प्रतिक्रियाओं के प्रायोगिक निष्कर्षों को मान्य किया गया है, इसलिए, एक विश्वसनीय संख्यात्मक मॉडल की स्थापना की।

टीपी संमिश्र लामिनेट्स के कम वेग प्रभाव (एलवीआई) प्रतिक्रिया पर कपड़ा वास्तुकला और संकरण के प्रभाव को निर्धारित करने के लिए प्रायोगिक जांच की जाती है। 240 जूलस के ऊर्जा स्तर पर ड्रॉप-भार प्रभाव उपकरण का उपयोग करके एलवीआई परीक्षण आयोजित किए जाते हैं। टीपी कंपोजिट के एलवीआई प्रतिक्रिया की तुलना शिखर बल, ऊर्जा अवशोषण और क्षति के पैटर्न के मुकाबले की जाती है। सजातीय कंपोजिट के एलवीआई प्रतिरोध 2 डी से 3 डी कंपोजिट (चरण-1) से बढ़ा है, जो कि कपड़े वास्तुकला के प्रभाव को दर्शाता है। हाइब्रिडिजेशन ने भी समृद्ध 2 डी / 3 डी कंपोजिट (चरण-2) की कम अव्यवस्थित घनत्व के ऊर्जा अवशोषण क्षमता में काफी सुधार किया है। हाइब्रिडिजेशन के कारण क्रमशः पीक बल और ऊर्जा अवशोषण के मामले में, कम अखाड़ा घनत्व वाले केवलर कंपोजिट का प्रभाव प्रतिरोध 45% से 51% और 23% से 26% तक बढ़ जाता है।

बैलिस्टिक प्रभाव परीक्षण, एनआईजे-एसटीडी -0106.01 प्रकार के साथ एक प्रभाव वेग रेंज के लिए 365 एम / एस से 438 एम / एस के बीच मानक परीक्षण सुविधाओं का उपयोग करते हुए सजातीय और हाइब्रिड कवच पैनलों पर प्रकार IIIA धमकी स्तर 9 मिमी पूर्ण धातु जैकेट (एफएमजे) प्रदान करता है। । क्षति के

पैटर्न, अवशिष्ट वेग और बैलिस्टिक सीमा को प्रयोगों से मापा जाता है। बैलिस्टिक परीक्षण के परिणाम बताते हैं कि केवलर समरूप कवच पैनलों (चरण -1) के मामले में, शस्त्रों की समान अखाड़ा घनत्व के लिए, 2 डी कवच पैनलों को 3 डी आर्मर्स की तुलना में प्रेरित क्षति को प्रभावित करने की अधिक संभावना है। 3 डी-ओ और 3 डी-ए (चरण -1) के फैब्रिक आर्किटेक्चर के साथ केवलर समरूप समग्र बख्तरबंद 9 मिमी एफएमजे प्रक्षेप्य का सामना करने में सक्षम हैं, जबकि 2 डी सादे बुना कवच असफल हैं। सोलह परत केवलर 3 डी सजातीय कवच पैनल एनआईजे-एसटीडी -0106.01 प्रकार IIIA (426 ± 15 मी / एस) द्वारा निर्धारित गति श्रेणी के भीतर शून्य विरूपण का प्रदर्शन किया। हाइब्रिड कवच पैनल (चरण -2) के मामले में, सममित बख्तरबंद पैनल 415 मीटर / एस की प्रभाव वेग तक 9 मिमी एफएमजे को झेलने में सक्षम है, जबकि गैर-सममित कवच पैनल 365 मीटर / सेकंड के प्रभाव वेग में विफल रहा है 395 मी / एस तक हालांकि, सूक्ष्म सेलुलर शीट (1.56 किलो) के साथ हाइब्रिड कवच पैनल ने सोलह परत केवलर 3D समरूप कवच पैनल (1.86 किग्रा) की तुलना में वजन में 15.67% की कमी के साथ पीछे के चेहरे पर शून्य विरूपण का प्रदर्शन किया।

बैलिस्टिक सीमा वेग, अवशिष्ट वेग और विफलता मोड के लिए एक अनुमान प्राप्त करने के लिए एएनएसवाईएस-एयूटीओडीएनएन v। 14.0, 14.5 का प्रयोग करके हाइड्रोकाइड सिमुलेशन किया जाता है। वर्तमान में निर्मित 2 डी / 3 डी टीपी कंपोजिट के यांत्रिक गुणों को मान्य करने के लिए, प्रायोगिक लक्षण वर्णन से प्राप्त सामग्री स्थिरांक को लागू करके हाइड्रोकाइड सिमुलेशन में एक भौतिक मॉडल विकसित किया गया है। सिमुलेशन से प्राप्त होने वाले बाद के प्रभाव वाले हानि पैटर्न की तुलना सिमुलेशन के प्रदर्शन का आकलन करने के लिए प्रयोगात्मक परिणामों से की जाती है। हाइड्रोकाइड सिमुलेशन और प्रयोगात्मक परिणामों के बीच अच्छे संबंध, क्रमशः चरण -1 और चरण -2 के बख्तरबंद के लिए 3.32% से 6.66% और 3.16% से 7.67% के अंतर के साथ असफलता मोड और नुकसान पैटर्न के मामले में क्रमशः मनाया जाता है। कार्यान्वित भौतिक मॉडल को शेष अवक्षेपण और बैलिस्टिक सीमा को सही ढंग से अनुमान लगाने में सक्षम है। सिमुलेशन से

अनुमानित बैलिस्टिक सीमा चरण -1 कवचरों के लिए 376 एम / एस से 470 एम / एस और 307 एम / एस से 490 मीटर / फेज -2 बख्तरबंद के लिए होती है।

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Nomenclature

List of symbols

$\hat{\theta}_m$	Melting temperature
ϵ_{ave}	Average strain
ϵ_{ij}^d	Deviatoric strain
ϵ_{eff}	Effective strain for erosion
$\bar{C}^k$	Elastic stiffness matrix
$\dot{\bar{\epsilon}}^{pl}$	Equivalent plastic strain rate
Γ	Grüneisen gamma
$\dot{\epsilon}_p$	Strain rate
ϵ_{vol}	Volumetric strain
$\bar{\sigma}$	Yield stress in Johnson-Cook model
$e_r(\epsilon_{vol})$	Energy-volume relation
$P_r(\epsilon_{vol})$	Pressure-volume relation
11	warp direction
12, 23, 13,	in-plane directions
22	weft direction
33	through the thickness direction
C_0	Bulk acoustic sound speed
C_{ij}	Stiffness matrix
d	depth of the cone
D_i	Damage initiation

E	Young's modulus (GPa, MPa)
E_{abs}	Energy absorption (J)
E_c	Compressive modulus (MPa)
E_i	Impact Energy (J)
G	Shear modulus (GPa)
G_0	initial shear modulus
K	Effective bulk modulus
KE_i	Initial kinetic energy (J)
KE_r	Residual kinetic energy (J)
k^{th}	Number of the lamina within the principal coordinate system
m_p	Mass of the projectile (g)
P	Equivalent pressure
P_{max}	Peak force or maximum load (kN)
T	Temperature
t	Thickness of the laminate (mm)
T^*	Transformation matrix
U_c	compressive strength (MPa)
U_t	Tensile strength (MPa)
V_{50}	Ballistic limit velocity from experiments (m/s)
V_{bl}	Ballistic limit velocity from simulations (m/s)
V_f	Fiber volume fraction
v_i	Incident/initial impact velocity (m/s)
v_r	Residual velocity (m/s)
W_c	Weight of composite
W_f	Weight of fibers
Y	Yield strength

Y_A	Thermal yield strength
a	Residual shear stiffness
γ_{ij}	Component shear strain
ε_c	failure strain in compression
ε_{ij}	Component of principal strain
ε_P	Equivalent plastic strain
ε_t	Failure strain in tension
θ_k	angle of the material direction
ν	Poissons ratio
ϱ	fabric areal density
ϱ_{3D-A}	3D-A fabric areal density
ϱ_c	Density of composite (g/cm ³)
ϱ_f	Density of fiber (g/cm ³)
σ_{ij}	Component of principal stress
τ_{ij}	Component of shear stress component shear strain

List of abbreviations

2D	Two-dimensional
2D-P	Two-dimensional plain woven (Kevlar, Phase-1)
3D	Three-dimensional
3D-A	Three-dimensional angle interlock (Kevlar, Phase-1)
3D-O	Three-dimensional orthogonal (Kevlar, Phase-1)
AP	Armour Piercing
ASTM	American Society for Testing Materials
B3D	Basalt 3D-A (reduced GSM, Phase-2)
BD	Damage diameter on the back face

BPL	Basalt 2D-plain (reduced GSM, Phase-2)
DAS	Data Acquisition System
DEF	Deformation
DMRL	Defence Metallurgical Research Laboratory
DRDO	Defence Research and Development Organization
EOS	Equation of State
FD	Damage diameter on the front face
FE	Finite Element
FMJ	Full Metal Jacket
FP	Full perforation/penetration
FSP	Fragment Simulating Projectile
GSM	Grams per Square Meter
H-1	Non-symmetric hybrid armor
H-2	Symmetric hybrid armor
H-3	Hybrid armor with MCS
H3D	Hybrid 3D-A (reduced GSM, Phase-2)
HAP	Hard Armor Panel
HMPE	High Molecular Polyethylene
HP-1	Hybrid-1 (alternate Kevlar and basalt yarns, reduced GSM, Phase-2)
HP-2	Hybrid-2 (basalt yarns in the warp and Kevlar yarns in the weft directions, reduced GSM, Phase-2)
IIT	Indian Institute of Technology
JSP	Jacketed Soft Point
K3D	Kevlar 3D-A (reduced GSM, Phase-2)
KCF	Kevlar Commercial Fabric
KPL	Kevlar 2D-plain (reduced GSM, Phase-2)

LRHV	Long Rifle High Velocity
LVI	Low Velocity Impact
MAg	Maleic Anhydride Grafted
MCS	Micro-cellular Sheet
ND	Zero deformation
NIJ	National Institute of Justice
P-1	Armor with 16 layer Kevlar 2D-P fabrics
P-2	Armor with 8 layer Kevlar 3D-O fabrics
P-3	Armor with 8 layer Kevlar 3D-A fabrics
P-4	Armor with 12 layer Kevlar 3D-O fabrics
P-5	Armor with 12 layer Kevlar 3D-A fabrics
P-6	Armor with 16 layer Kevlar 3D fabrics (4: 3D-A and 12: 3D-O)
PEEK	Polyether–ether–ketone
PP	Polypropylene
PF	Partial perforation/penetration
PPS	Polyphenylene sulfide
RN	Round Nose
SAP	Soft Armor Panel
SEM	Scanning Electron Microscopy
SWC	Semi-Wad cutter
TBRL	Terminal Ballistics Research Limited
TP	Thermoplastic
TS	Thermoset
UD	Uni-directional
USA	United States of America
UTM	Universal Testing Machine