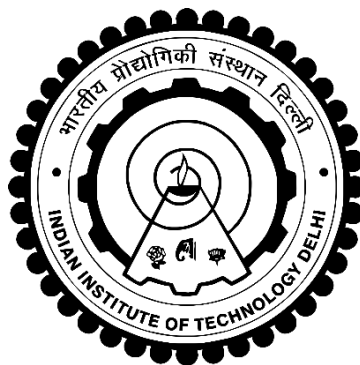


**EXPERIMENTAL AND NUMERICAL STUDY
OF BODY ARMOR OF ULTRA HIGH
MOLECULAR WEIGHT POLYETHYLENE**

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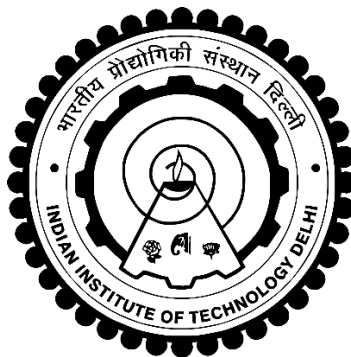
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Submitted

in fulfilment of requirements for the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

MAY 2026

Dedicated

To My Brother

Pastor Percy Solomon

CERTIFICATE

This is to certify that the thesis entitled, '**Experimental and Numerical Study of Body Armor of Ultra High Molecular Weight Polyethylene**' submitted by **Mr. Joseph Solomon** to the **Indian Institute of Technology Delhi** for the award of the degree of **Doctor of Philosophy** embodies original research work carried out by him under our supervision. In my opinion, the thesis work meets the requisite standards, and the candidate is worthy of consideration for the degree of Doctor of Philosophy in accordance with the institute's regulations. The contents of this thesis have not been submitted to any other University or Institute for the award of any degree or diploma.

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ABSTRACT

The quest for lightweight, high-performance ballistic protection has accelerated the adoption of Ultra High Molecular Weight Polyethylene (UHMWPE) laminates in modern body armor systems. This study presents an integrated experimental and numerical investigation into the ballistic behavior of UHMWPE-based armor panels under both single and multiple projectile impacts. Material modeling strategies were established to capture the orthotropic plasticity behavior of UHMWPE laminates, while Smooth Particle Hydrodynamics (SPH) was implemented to simulate realistic projectile deformation under impact loading. The findings of low velocity impact on hard armor panel (HAP) and soft armor panel (SAP) highlight the dominant role of plastic deformation in influencing the behavior of UHMWPE during impact. These results underscore the necessity of incorporating plasticity into the constitutive modeling of UHMWPE composites for accurate prediction of impact behavior.

Numerical modeling and ballistic evaluation of a multilayer UHMWPE-based body armor system consisting of HAP, SAP, foam and clay is carried out to meet Level 3 ballistic protection standards. Simulations closely matched experimental results, with backface signatures of 14.8 mm (simulated) and 15.6 mm (experimental). The multi-hit response of the ceramic/UHMWPE armor against steel core projectiles is analyzed, with simulations predicting BFS values closely matching with experiments. The use of hexagonal ceramic tiles wrapped in Kevlar epoxy effectively localized damage, preventing radial cracks and confining failure to individual tiles is also examined. The energy absorption by each component of the armor is also discussed.

सार

हल्के तथा उच्च-प्रदर्शन बैलिस्टिक सुरक्षा की आवश्यकता ने आधुनिक बॉडी आर्मर प्रणालियों में अल्ट्रा हाई मॉलेक्युलर वेट पॉलीएथिलीन लैमिनेट्स के उपयोग को तेज़ी से बढ़ावा दिया है। इस अध्ययन में एकीकृत प्रायोगिक तथा संख्यात्मक विश्लेषण प्रस्तुत किया गया है, जिसमें UHMWPE-आधारित आर्मर पैनलों के बैलिस्टिक व्यवहार का एकल तथा बहु-प्रक्षेप्य प्रभावों के अंतर्गत अध्ययन किया गया है।

UHMWPE लैमिनेट्स के ऑर्थोटॉपिक प्लास्टिसिटी व्यवहार को सटीक रूप से दर्शाने के लिए सामग्री मॉडलिंग रणनीतियाँ विकसित की गईं, जबकि प्रभाव के दौरान प्रक्षेप्य के यथार्थ विकृति को अनुकरण करने हेतु स्मूद पार्टिकल हाइड्रोडायनेमिक्स (SPH) विधि का उपयोग किया गया। हार्ड आर्मर पैनल (HAP) और सॉफ्ट आर्मर पैनल (SAP) पर निम्न वेग प्रभाव के परिणामों से यह स्पष्ट हुआ कि UHMWPE के प्रभाव व्यवहार में प्लास्टिक विकृति की प्रमुख भूमिका होती है। ये निष्कर्ष UHMWPE कॉम्पोजिट्स के संवैधानिक मॉडलिंग में प्लास्टिसिटी को शामिल करने की आवश्यकता को रेखांकित करते हैं, ताकि प्रभाव व्यवहार का सटीक पूर्वानुमान किया जा सके।

इसके अतिरिक्त, HAP, SAP, फोम तथा क्ले से युक्त बहु-परत UHMWPE-आधारित बॉडी आर्मर प्रणाली का संख्यात्मक मॉडलिंग एवं बैलिस्टिक मूल्यांकन किया गया, ताकि इसे लेवल 3 बैलिस्टिक सुरक्षा मानकों के अनुरूप बनाया जा सके। सिमुलेशन परिणाम प्रायोगिक परिणामों के साथ अत्यंत निकट पाए गए, जहाँ बैकफेस सिग्नेचर (BFS) के मान 14.8 मिमी (सिमुलेशन) और 15.6 मिमी (प्रयोग) प्राप्त हुए।

सिरेमिक/UHMWPE आर्मर की बहु-प्रहार (multi-hit) प्रतिक्रिया का भी स्टील कोर प्रक्षेप्यों के विरुद्ध विश्लेषण किया गया, जिसमें सिमुलेशन द्वारा प्राप्त BFS मान प्रायोगिक मानों के साथ अच्छी संगति में पाए गए। केवलर-एपॉक्सी में लिपटे षट्कोणीय सिरेमिक टाइलों के उपयोग से क्षति का स्थानीयकरण प्रभावी रूप से हुआ, जिससे रेडियल दरारों को रोका जा सका और विफलता को व्यक्तिगत टाइलों तक सीमित रखा गया। इसके अतिरिक्त, आर्मर के प्रत्येक घटक द्वारा अवशोषित ऊर्जा का भी विस्तृत विश्लेषण किया गया है।

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LIST OF SYMBOLS

ρ	Material density
t	Time
V_i	Velocity component in the i-th direction
x_i	Spatial coordinate in the i-th direction
σ_{ij}	Stress tensor component (stress in i direction on a plane normal to j)
f_i	External force component in the i-th direction
e	Specific internal energy
$\sigma_{11}, \sigma_{22}, \sigma_{33}$	Normal stress components in material principal directions
$\sigma_{23}, \sigma_{31}, \sigma_{12}$	Shear stress components
ε_{ij}	Total strain tensor component
ε^d_{ij}	Deviatoric strain tensor component
ε_{vol}	Volumetric strain
C_{ij}	Stiffness matrix constants (material elastic constants)
P	Pressure
v	Specific volume
$\Gamma(v)$	Grüneisen coefficient
$e_r(v)$	Reference internal energy

$P_r(v)$	Reference pressure
a_{ij}	Material constants defining anisotropy in quadratic yield surface
k	State variable defining yield surface limit
$d\epsilon_{p,ij}$	Incremental plastic strain
λ	Plastic multiplier (plastic factor)
$\bar{\sigma}$	Effective stress
$d\bar{\epsilon}^p$	Incremental effective plastic strain
W_p	Plastic work
S_{ii}, S_{ij}	Failure strength of the material in respective directions
D_{ii}	Damage variable
L	Characteristic length
ϵ_{cr}	Crack strain (strain above failure initiation strain)
$G_{f,ii}$	Fracture energy in direction of damage
G	Shear modulus
G_0	Reference shear modulus at $T = 300 \text{ K}$, $P = 0$
G'_p	Pressure derivative of shear modulus (dG/dP)
G'_t	Temperature derivative of shear modulus (dG/dT)
Y	Yield strength
Y_0	Reference yield strength at $T = 300 \text{ K}$, $P = 0$
Y'_p	Pressure derivative of yield strength (dY/dP)

Y'_t	Temperature derivative of yield strength (dY/dT)
T	Temperature
η	Compression ratio (initial specific volume / current specific volume)
ε	Strain
ε_i	Initial equivalent plastic strain
σ_n	Normal stress
σ_s	Shear stress
S_n	Normal failure strength
S_s	Shear failure strength
$f(x)$	Function of spatial coordinate
Ω	Sub-domain of influence
$W(x - x_i, h)$	Kernel (smoothing) function
h	Smoothing length (defines extent of sub-domain influence)
q	Non-dimensional distance ratio
ξ	Dimensionality of the problem (1D, 2D, or 3D)
x_i	Position of particle i
Y	Yield stress
A	Initial yield strength parameter
B	Strain hardening modulus
N	Hardening exponent

C	Strain-rate sensitivity coefficient
M	Thermal softening exponent
T_M	Melting temperature
T_R	Reference temperature
$\varepsilon_{\text{eff}}^p$	Effective plastic strain
$\dot{\varepsilon}_{\text{eff}}^p$	Plastic strain rate
$\dot{\varepsilon}_0$	Reference strain rate
D	Cumulative damage variable
ε^F	Failure strain
D_1 to D_5	Johnson–Cook failure parameters
σ_{eff}	effective stress
Ψ	Strain energy potential
$\bar{I}_1$	First deviatoric invariant of the Cauchy–Green strain tensor
$\bar{I}_2$	Second deviatoric invariant of the Cauchy–Green strain tensor
J	Determinant of the deformation gradient (volume ratio)
C_{10}, C_{01}, C_{11}	Mooney–Rivlin material constants
K_1	Bulk modulus
$K_2,$ K_3	Equation of state pressure coefficients
β	Bulking factor

LIST OF ABBREVIATIONS

UHMWPE	Ultra High Molecular Weight Polyethylene
HAP	Hard Armor Panel
SAP	Soft Armor Panel
BFD	Back Face Deformation
BFS	Back Face Signature
SPH	Smooth Particle Hydrodynamics
DIC	Digital Image Correlation
BIS	Bureau of Indian Standards
FE	Finite Element
HSC	Hardened Steel Core
API	Armor Piercing Incendiary
HEL	Hugoniot Elastic Limit
NATO	North Atlantic Treaty Organization
FMJ	Full Metal Jacket
CT	Computed Tomography
MSC	Mild Steel Core
RP	Roma Plastilina (ballistic clay)

NIJ	National Institute of Justice
KE	Kinetic Energy
SK76	Dyneema SK76 fiber
FSP	Fragment Simulating Projectile
APM2	Armor Piercing M2 (Projectile)
CFRP	Carbon Fiber Reinforced Polymer
EOS	Equation of State
CAD	Computer-Aided Design
EPE	Expanded Polyethylene
EPS	Expanded Polystyrene