LOW VELOCITY IMPACT STUDY ON BASALT FIBER REINFORCED UNI-DIRECTIONAL AND PLAIN WOVEN COMPOSITES: MECHANICAL CHARACTERIZATION AND NUMERICAL MODELING

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by

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Dedicated to

respected Guru Ji

Shri Kamal Singh Yadav Ji

and my parents

Shri Arun Kumar Gupta & Smt. Neeru Gupta

CERTIFICATE

This is to certify that the thesis entitled, **"Low Velocity Impact Study on Basalt Fiber Reinforced Uni-Directional and Plain Woven Composites: Mechanical Characterization and Numerical Modeling"** submitted by **Mr. Mohit Gupta** for the award of degree of **Doctor of Philosophy** to the **Indian Institute of Technology Delhi** is a record of bonafide research work carried out by him under our guidance and supervision. **Mr. Mohit Gupta** has fulfilled all the prescribed requirements and the thesis is, in our opinion, worthy of consideration for the degree of Doctor of Philosophy in accordance with the regulations of the Institute. The contents of 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.

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ABSTRACT

Composites are made up of two or more constituent materials in order to utilize the advantages of both the constituents to provide excellent properties like high specific stiffness, high specific strength, good corrosion and fatigue resistance etc. However, their sensitivity to impact damage arising due to tool drops, hail stones, bird strike etc. poses serious threats as the damage is tough to detect from visual inspection. Besides impact use of less environmental friendly fibers and matrix materials are also a cause of concern in use of composites. Basalt, a mineral fiber obtained from rocks requires less chemicals during processing compared to glass and carbon, but its composites are less explored in their mechanical performance and low velocity impact (LVI) behavior. The present thesis emphasizes on developing constitutive models for Uni-Directional (UD) and Plain Woven (PW) lamina and their mechanical characterization for providing inputs to the proposed models to simulate numerically the response under LVI cross-ply and PW laminates.

Tensile and compressive tests were conducted on UD and PW laminates to evaluate the moduli and strengths of lamina in longitudinal and transverse directions. Intralaminar fracture toughness in tension and compression were obtained using Compact Tension (CT) and Compact Compression (CC) tests. The interlaminar fracture toughness energies were determined in Mode-I and Mode-II testing configuration using double cantilever (DCB) and end-notch flexural (ENF) tests to model the delamination between plies. Shear tests were performed to measure the modulus, shear strength and the non-linear behavior arising from both damage and plasticity. Cyclic off-axis tests were performed and using effective stress concept damage was decoupled from the plasticity in the non-linear stress strain curves under off-axis loadings to obtain the parameter of general quadratic yield function.

Continuum Damage Mechanics (CDM) based elasto-plastic constitutive laws were developed for both UD and PW lamina using a three-dimensional plastic potential function. The elastic stiffness in different directions was degraded once damage initiation criteria were satisfied. In UD lamina model damage was assumed in principal material directions and damage variable in shear was a function of the damage variables in these directions. In PW lamina variables independent shear damage variables and damage laws were used. Exponential damage evolution laws used material softening parameter '*m*' for a particular mesh size was determined for principal directions in tension and compression its value was related to the experimentally obtained intralaminar fracture toughness. Delamination between plies was modeled using surface based cohesive zone modeling (CZM) for predicting delamination damage between plies. Experimentally determined interlaminar fracture energies were used in CZM. These constitutive models for UD and PW materials were implemented in a user subroutine, VUMAT for ABAQUS/Explicit and used to predict the force-time, displacement response of laminates of these materials under LVI.

LVI experiments at different impactor velocities were also performed on cross-ply and PW laminates using drop weight impact tester. The force-time and displacement response from the simulations matched with those obtained from experiments. The extent of damage from simulations also matched well with damage measured using ultrasonic C scan. The constitutive models for UD and PW lamina were thus validated.

सार

उच्च विशिष्ट कठोरता, उच्च विशिष्ट शक्ति, अच्छा संक्षारण और थकान प्रतिरोध आदि जैसे उत्कृष्ट गुण प्रदान करने के लिए दोनों घटकों के फायदे का उपयोग करने के लिए कंपोजिट दो या अधिक घटक सामग्रियों से बना है। हालांकि, उपकरण के गिरने से, ओलों की मार, चिडियो के टकराव इत्यादि के होने वाले इम्पैक्ट क्षति से उनकी संवेदनशीलता का दृश्य निरीक्षण से पता लगपना कठिन होता है । कम पर्यावरण के अनुकूल फाइबर और मैट्रिक्स सामग्री के उपयोग का प्रभाव भी कंपोजिट के उपयोग में चिंता का कारण है। बसाल्ट, चट्टानों से प्राप्त खनिज फाइबर को ग्लास और कार्बन की तुलना में प्रसंस्करण के दौरान कम रसायनों की आवश्यकता होती है, लेकिन इसके कंपोजिट उनके यांत्रिक प्रदर्शन और कम वेग प्रभाव (LVI) व्यवहार के क्षेत्र में काम खोजबीन हुई है। वर्तमान थीसिस ने यूनी-दिशात्मक (UD) और प्लेन वोवन (PW) लैमिना के लिए संवैधानिक मॉडल विकसित करने पर जोर दिया और प्रस्तावित मॉडल को इनपुट प्रदान करने के लिए उनके यांत्रिक लक्षण वर्णन के लिए संख्यात्मक रूप से LVI क्रॉस-प्लाई और पPW लैमिनेट्स के तहत प्रतिक्रिया का अनुकरण किया।

लोंगितुंडिनल और ट्रांस्वर्स दिशाओं में लामिना की मोडुली और ताकत का मूल्यांकन करने के लिए UD और PW लैमिनेट्स पर टेंसाइल और कम्प्रेस्सिव परीक्षण किए गए थे। इंट्रालामिनर फ्रैक्चर क्रूरता टेंसाइल और कम्प्रेस्सिव में कॉम्पैक्ट टेंशन (CT) और कॉम्पैक्ट कम्प्रेशन (CC) परीक्षणों का उपयोग करके प्राप्त किया गया था। इंटरलामिनर फ्रैक्चर टफनेस की ऊर्जाएँ मोड-I और मोड- II परीक्षण कॉन्फ़िगरेशन में डबल कैंटीलीवर (डीसीबी) और एंड-नॉट फ्लेक्सुरल (ईएनएफ) परीक्षणों का उपयोग करके प्लाइज़ के बीच का डीलैमिनाशन मॉडल किया । मॉडुलुस, शियर ताकत और नॉन-लीनियर व्यवहार जो की क्षति और प्लास्टिसिटी से उत्पन्न होते हैं इनको मापने के लिए शियर परीक्षण किए गए थे । चक्रीय ऑफ-एक्सिस परीक्षण प्रभावी तनाव कांसेप्ट का इस्तेमाल

करके किए गए और क्षति एवम प्लास्टिसिटी को गैर-रैखिक तनाव में अलग करने के लिए सामान्य क्वाड्रैटिक यील्ड फ़ंक्शन के पैरामीटर को प्राप्त किया गया। कॉन्टिनम डैमेज मैकेनिक्स (सीडीएम) आधारित इलास्टो-प्लास्टिक संविधान तीन-आयामी प्लास्टिक संभावित फ़ंक्शन का उपयोग करके UD और PW लैमिना दोनों के लिए कानून विकसित किए गए थे। एक बार जब क्षति की शुरुआत सुनिश्चित हो गयी, तब विभिन्न दिशाओं में इलास्टिक कठोरता को डीग्रेड किया गया था। UD लामिना मॉडल में क्षति को मुख्य भौतिक दिशाओं में माना गया था और शियर में क्षति वेरिएबल इन दिशाओं में क्षति वेरिएबल पर आधारित है । PW लैमिना वेरिएबल्स में स्वतंत्र शियर क्षति वेरिएबल्स और क्षति कानूनों का उपयोग किया गया था। एक विशेष मेष आकार के लिए सामग्री की नरमी पैरामीटर 'm' का उपयोग किए जाने वाले एक्सपोनेंशियल क्षति ऐवोलुशन कानून तनाव में प्रमुख निर्देशों के लिए निर्धारित किया गया था और इसका मूल्य प्रयोगात्मक रूप से प्राप्त इंट्रालमिनर फ्रैक्चर टफनेस से संबंधित था। पिलाइज़ के बीच डीलैमिनाशन मॉडल करने के लिए सरफेस बेस्ड कोहेसिव ज़ोन मॉडलिंग (CZM) का उपयोग डीलैमिनाशन क्षति का अनुमान लगाने के लिए किया गया । CZM में प्रयोगात्मक रूप से निर्धारित इंटरलामिनर फ्रैक्चर ऊर्जा का उपयोग किया गया था। UD और PW सामग्रियों के लिए इन संवैधानिक मॉडल को एक उपयोगकर्ता सबरूटीन, VUMAT (ABAQUS/Explicit) में लागू किया गया और इससे LVI के तहत बल-समय, विस्थापन प्रतिक्रिया का अनुमान करने के लिए उपयोग किया गया ।

LVI प्रयोगों में अलग-अलग इम्पैक्टर वेगों से क्रॉस-प्लाई और PW लैमिनेट्स पर ड्रॉप वेट इम्पैक्ट टेस्टर का उपयोग करके किया गया। प्रयोगों और सिमुलेशन से प्राप्त होने वाले बल-समय और विस्थापन प्रतिक्रिया का मेल देखा गया। सिमुलेशन से नुकसान की सीमा और अल्ट्रासोनिक सी स्कैन के उपयोग से मापी क्षति के साथ अच्छी तरह से मेल खाती है। UD और PW लैमिना के लिए संवैधानिक मॉडल की मांन्यता इस प्रकार साबित की गयी ।

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A_D	Damaged area of the material
A_0	Total cross section area
D	Scalar damage variable
σ	Nominal stress
ε	Total strain
σ_e	Effective stress
E_0	Initial stiffness of the isotropic material
E_D	Effective modulus due to degradation of an isotropic material
$\mathbf{S}_0$	Compliance tensor
σ_{11} σ_{22} σ_{33}	Nominal stresses in longitudinal, transverse and out of plane direction
σ_{12} σ_{13} σ_{23}	Shear stresses for in-plane and out of plane directions
E_{ij}	Young's modulus
G_{ij}	Shear modulus
ν_{ij}	Poisson's ratio
$\mathbf{C}_0$	Elastic stiffness tensor
M	Damage effect tensor
I	Second order identity tensor
D_{11} D_{22} D_{33}	Damage variables in plane fiber, in plane transverse and out of plane transverse directions
D_{44} D_{55} D_{66}	Damage variables for in-plane shear, and out of plane shear directions
σ_{e11} σ_{e22} σ_{e33}	Effective stresses in longitudinal, transverse and out of plane direction
σ_{e12} σ_{e13} σ_{e23}	Effective stresses for in plane transverse and out of plane transverse directions
σ_s	Tensile strength
ε_f	Failure strain
R_{1T}	Longitudinal direction tension failure criterion
R_{2T}	Longitudinal direction compressive failure criterion

S_{1T}	Longitudinal tensile strength
S_{2T}	Transverse tensile strength
S_{12}	In-plane shear strength
S_{13} S_{23}	Out-of-plane shear strength
S_{1C}	Longitudinal Compressive strengths
S_{2C}	Transverse compressive strengths
S_{3C}	Out-of plane compressive strengths
R_{1C}	Longitudinal direction compression failure criterion
R_{2C}	Transverse direction compression failure criterion
R_{3C}	Out-of plane direction compression failure criteria
n,l and t	Refers to normal, longitudinal and tangential direction with respect to the fracture plane direction
θ	Angle of plane for matrix dominated failure
a_{66}	Single parameter plastic variable
$\overline{\sigma}_e$	Effective equivalent stress
$\overline{\sigma}_f$	Effective flow stress
$(\sigma_e)_{xx}$	Effective applied stress
ε_x^p	Plastic strain in the uniaxial direction of the specimen
F_{yield}	Plastic potential function
$\overline{\sigma_{e\,f}}$	Effective flow stress
$\overline{\varepsilon}^p$	Equivalent plastic strain
ε_{xx}	Longitudinal strains
d_i	Failure functions
d	Damage variable
m_i	Material softening parameter for failure mode
e	Napier’s constant
m	Material softening parameter
1T,1C, 2T, 2C 3C	Longitudinal tension, longitudinal compression, transverse tension, transverse compression, out of plane compression.

Γ_C	Intralaminar fracture toughness
L_c	Characteristic length of the element for a particular damage mode
Γ_C^f	Intralaminar fracture toughness in fiber direction
Γ_C^m	Intralaminar fracture toughness in matrix direction
ε	Total strain
ε^e	Elastic strains
ε^p	Plastic strain

LIST OF ABBREVIATIONS

LVI	Low velocity impact
UD	Uni-directional
PW	Plain woven
BUD	Basalt uni-directional
BPW	Basalt plain woven
FRP	Fiber reinforced polymer
BFRP	Basalt fiber reinforced polymer
CFRP	Carbon fiber reinforced polymer
DIC	Digital image correlation
FE	Finite element
BVID	Barely visible impact damage
UTM	Universal testing machine
DCB	Double cantilever beam
ENF	End notch flexure
CT	Compact tension
CC	Compact compression
CDM	Continuum damage mechanics
CZM	Cohesive zone modeling
HVI	High velocity impact
DTL	Damage threshold level
CAI	Compression after impact
ILSS	Interlaminar shear strength
VARIM	Vacuum assisted resin infusion molding
ASTM	American society for testing and material
LED	Light-emitting diode
CCD	Charge-coupled device
AOI	Area of interest
CLC	Combined loading compression
MBT	Modified beam theory