LOW VELOCITY IMPACT ON GLASS FIBRE REINFORCED EPOXY COMPOSITES: EXPERIMENTS AND SIMULATION

KIRAN KUMAR NAMALA

DEPARTMENT OF APPLIED MECHANICS

INDIAN INSTITUTE OF TECHNOLOGY DELHI

JANUARY 2016

LOW VELOCITY IMPACT ON GLASS FIBRE REINFORCED EPOXY COMPOSITES: EXPERIMENTS AND SIMULATION

by

KIRAN KUMAR NAMALA

Department of Applied Mechanics

Submitted

in fulfilment of the requirements of the degree of

Doctor of Philosophy

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

January 2016

CERTIFICATE

This is to certify that the thesis entitled "**Low Velocity Impact on Glass Fiber Reinforced Epoxy Composites : Experiments and Simulation**" being submitted by Mr**. Kiran Kumar Namala** to the **Indian Institute of Technology Delhi** for the award of degree of Doctor of Philosophy is a record of bonafide research work carried out by him under our supervision and guidance. The thesis, in our opinion has reached the standard of fulfilling the requirements for the award of degree of **Doctor of Philosophy**.

The research report and the results presented in this thesis have not been submitted in part or full to any other university or institute for the award of any degree or diploma.

Dr. Puneet Mahajan
Professor
Department of Applied Mechanics
Indian Institute of Technology Delhi
New Delhi 110016

Dr. Naresh Bhatnagar
Professor
Department of Mechanical Engineering
Indian Institute of Technology Delhi
New Delhi 110016

Date :

ACKNOWLEDGEMENTS

I would like to express sincere and deepest gratitude to my supervisor honourable **Prof. Puneet Mahajan** for his valuable guidance who taught me the knowledge, guided my study, helped me to develop the skills, and especially trained me to be a better professional in thinking, executing, writing, and presenting. I am thankful to honourable **Prof. Naresh Bhatnagar** for guiding me through this work with their valuable insight and supervising my thesis and encouragement throughout the programme. I completed my project because of their precious time, even during their holidays. No amount of words would suffice in return to their favour and cooperation. I am grateful to professors in all respects.

I thank **Prof. Suhail Ahmed, Dr. Maloy Kumar Singha** and **Prof. R. Alagirusamy**, the members of my review committee for their valuable suggestions during my presentations and examinations were very useful in giving direction to my research work. **Prof. Sanjeev Sanghi** and all the faculty members of the department who supported and helped me in accomplishing research activities at IIT Delhi.

I am fortunate to have my friends **Rajneesh Sharma** and **Nilamber Kumar Singh** by my side during the current research and the time spent with them was memorable. I also thank my friends in the department **(M.V. Rao, Praveen Pinnoji, Madhav Krishna, Ibrahim, Kallol Kahn, Ankur, Yaqoob, Hussain, Ajay, Atul, Prince, Anil Yadav, Anubhav Rawat, Sishodia, Aswani, Chaman, Hossein, Renjith, Yudhast and Shivdayal**) and other co scholars at various laboratories in Department of Applied Mechanics and at institute who made my life and research comfortable at IITD.

I thank **Dr. Sangeeta Khare, Mr. Harpreet Singh, Mr. Sanjay Singh and Mr. Mohit Gupta** for their valuable support during the submission. I thank technical staff Mr**. Anil**

Kumar and **Mr. Rishi Prakash** of Applied Mechanics Department in conducting the experiments, **Mr. Vijay** and **Mr. Tulsi Ram** of Mechanical Engineering department for their help in preparing moulds and composites.

I express my gratitude to **Prof. B. S. Chandrasekhar,** Dean for his co-operation during the submission process. I also feel it is important to mention the students, School of Engineering for their understanding during leave for my thesis submission.

I pay great respect to my parents, in-laws and relatives for their patience during my research. I accepted their tolerance with true and tough heart for my professional growth. I acknowledge my wife **Swathi** for her constant love, affection, support, inspiration and encouragement, whose love, wisdom and generosity have enriched my life. I wish to mention thanks to my younger brother **Mr. N S S R Kishore** who supported during the tough times to the need and deed. I acknowledge all my teachers and people who made me to think about research. I take this opportunity to thank all my other friends and well wishers who helped me directly or indirectly during this research work.

My apologies to my daughter **Sai Sakshi Sri** for not giving quality life and time to her.

Above all, the Almighty who made me go through various distinct phases and thoughts of philosophical life to unearth self. ***Ahambrahmasmi*** (Brhadaranyaka Upanishad 1.4.10).

KIRANKUMAR NAMALA

IIT DELHI

ABSTRACT

Composite material when used for specific stiffness and specific strength applications are susceptible to damage when subjected to impact loads. To understand the response of these materials under impact loading experiments and numerical simulations are performed in this work.

For simulating the response of composite laminate numerically properties such as moduli, strength and failure energies are needed which have to be determined experimentally. The properties of unidirectional composite such as tensile, compressive, shear, intra-laminar fracture toughness and interlaminar fracture toughness (mode I and mode II) are determined according to ASTM standards.The values of these properties are determined and compared with those available in the literature for similar fiber volume fraction. Iosipescu shear test was performed for finding shear modulus and shear strength. Three point bend test was done for finding fracture energy (G_I) in Mode I for matrix cracking and fiber failure (parallel and perpendicular to fiber orientation). The double cantilever beam (mode I) and the end notch flexure (mode II) tests were performed to determine interlaminar fracture toughness G_I and G_{II}. The determined properties were used in the numerical simulation of low-velocity impact laminates for unidirectional as well as cross-ply laminates. A continuum damage mechanics based constitutive law with provision for stiffness degradation of each lamina due to intra-laminar damage is used in the simulations. Intra-laminar damage initiation was modelled using Hashin's and Shurman-Puck failure criteria. Damage evolution for different intra-laminar failure modes are related to the strain. The constitutive material model was incorporated as a subroutine which was linked to a commercial Finite Element (FE) code.

Low Velocity Impact (LVI) experiments were performed on unidirectional laminate and cross-ply laminate of E-glass/epoxy composites. The energy, contact forces and displacement plots with respect to time were studied for the drop test. The damage observed as back face signature on the back face of both cross-ply and unidirectional laminate were plotted. The composite was speckled randomly and the impact phenomenon was recorded by using a high-speed camera. The DIC data on the surface of the plate was analyzed to obtain displacement and strains on the surface of the plate. The damage observed as back face signature on the back face of laminate, energy, contact forces and displacement plots with respect to time were determined and compared with FE results.

Key Words: Composites, Finite element simulation, Digital Image Correlation, damage, Low Velocity Impact.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

ε_f	Strain at failure
α	Angle of V-notch
α	Approach of two elastic bodies in contact
${}^{n}\bar{\sigma}_{yy}$	Average in plane transverse stress in n^{th} lamina
${}^{n}\bar{\sigma}_{xz}$	Average transverse shear stress in XZ plane in n^{th} lamina
${}^{n}\bar{\sigma}_{yz}$	Average transverse shear stress in YZ plane in n^{th} lamina
a	Crack length
a_0	Initial crack length
a_i	Acceleration
d	Depth of crack in the specimen
d_f^c	Damage variable for fiber compression
d_f^t	Damage variable for fiber tension
d_m^c	Damage variable for matrix compression
d_m^t	Damage variable for matrix tension
μ_t^n, μ_l^n	Friction coefficients
$\delta_m^{\max}$	Maximum effective separation value during loading
δ_m^f	Effective separation at complete damage
δ_m^0	Effective separation at damage initiation
ε_{11}^0	Strain at which damage initiates
ε_{11}^{ft}	Failure strain at fiber tension
ε_{11}^{fc}	Failure strain at fiber compression
α	Angle of Rotation about optical axis
α_0	Fracture angle
ρ	Density of composite body
δ	Load point displacement
δ	Deflection of the plate
β	Stereo angle
γ	Tilt angle
θ	Fracture angle

δ_n, δ_s, δ_t	Separation values of normal, shear and traction loading
$\delta_n^f, \delta_s^f, \delta_t^f$	Final relative displacements in normal, shear and traction.
δ_n^0, δ_s^0	Onset displacement at damage initiation
ξ, η, ζ	Curvilinear coordinate system of an iso-parametric element
ν_{12}	Poisson's ratio
ρ_c	Density of the composite
α_{cr}	Critical indentation depth
ρ_f	Density of the fiber
σ_i	Stresses in contracted notation
σ_e	Effective stress
ε_i	Strains in contracted notation
ν_{ij}	Poisson's ratio
ε_{ij}	Strain tensor
γ_{ij}	Strain tensor ($i\neq j$)
σ_{ij}	Stress tensor/ Stress component
τ_{ij}	Stress tensor ($i\neq j$)
τ	Interlaminar shear stress
α_m	Maximum indentation
Δ	Correction factor
Δt	Size of time step
[K], **K**	Stiffness matrix
[M], **M**	Mass matrix
b_i	Body force per unit volume
b	Specimen width
b	Distance between the notch roots
B	Thickness of specimen
C	Compliance
C_0, C_1, C_2, C_3, C_4,	Compliance coefficients
c_0, c_1, c_2, c_3, c_4	Calibration coefficients
C_{ij}	Stiffness

C_{ijkl}	Elasticity matrix in generalized Hooke's law for anisotropic
D	Scalar damage variable
E_{1}, E_{11}	Young's Modulus of the composite material along fiber
E_{2}, E_{22}	Young's Modulus of the composite material along transverse
E_{3}, E_{33}	Young's Modulus of the composite material in out of plane
E_{ij}	Young's moduli
e_M, e_D	Matrix cracking and delamination failure criteria identifiers
e_{xx}	Strain along fiber direction
F, F_c	Contact Force
fps	Frame per second
g	Acceleration due to gravity
g	Energy dissipated in softening per unit volume
G, G_f	Fracture energy per unit area of the composite
G_{1+}, G_{1-}	Fracture energy for longitudinal failure in tension and
G_{2+}, G_{2-}	Fracture energy for transverse failure in tension and
G_6	Fracture energy for transverse failure in shear
G_c	Critical fracture energy
G_{I}, G_{II}, G_{III}	Fracture energy in mode I, mode II, mode III
G_{ij}	Shear moduli
h	Drop height
h	Width of specimen
k	Stiffness of spring
K	Stiffness matrix
K_n, K_s, K_t	Stiffness in normal, shear and traction directions
L	Half of span length
l^*	Characteristic length
m	Meters
m/s	Metre/second
m_{1}, m_2	Mass of colliding spheres
m_c	Mass of composite

m_f	Mass of reinforcement
m_i, M, $M_{I,}$ m	Mass of impactor
M	Mass matrix
$m_{m,}$	Mass of matrix
mm	Millimetres
N	Newton
N_i	Standard continuous shape functions
n_c	Number of nodes in the element
N-m	Newton metre
P	Applied Load
S	Span of specimen length
S_{12}	In-plane shear strength
S_{11}^t	Longitudinal tensile strength
S_{11}^c	Transverse tensile strength
S_{22}^t	Transverse tensile strength
S_{23}^A	Shear strength in fracture plane
sec	Second(s)
S_i	Transverse shear strength (i = interlaminar)
S_{ij}	Compliances
t	Time
t, h	Thickness of specimen
T_{eff}	Effective traction stress at the damage initiation
t_n, t_s, t_t	Stress generated due to normal, shear and traction loading with
$\overline{t}_n$, $\overline{t}_s$, $\overline{t}_t$	Traction stress without damage
T_x, T_y, T_z	Components of resultant base distance between the cameras
t_n^0, t_s^0	Interface normal tensile strength and shear strength
U	Strain energy
${}^{t}u$ and ${}^{t+\Delta t}u$	Displacement at time *t* and *t*+*Δt*
${}^{t}\dot{u}$ and ${}^{t+\Delta t}\dot{u}$	Velocity at time *t* and *t*+*Δt*
${}^{t}\ddot{u}$ and ${}^{t+\Delta t}\ddot{u}$	Acceleration at time *t* and *t*+*Δt*

$\ddot{u}_I$	Acceleration of the impactor
v	Velocity
V_c	Volume of the composite
V_f	Volume fraction of fiber
V_m	Volume fraction of matrix
w	Displacement of a point
W	Width of the specimen
W	Length of specimen in shear test
x	Compressed length of spring during impact
X_1, Y_1, Z_1	Coordinate system of image plane of camera 1
X_2, Y_2, Z_2	Coordinate system of image plane of camera 2
X, X_c	In plane longitudinal tensile and compressive strength
Y, Y_c	In plane transverse tensile and compressive strength
Z, Z_c	Out of plane tensile and compressive strength

AOI	Area of Interest
ASTM	American Society for Testing and Materials
CMOD	Crack Mouth Opening Displacement
CMOS	Conducting Metal Oxide Semiconductor
DCB	Double Cantilever Beam
DIC	Digital Image Correlation
ENF	End Notch Flexure
LVI	Low Velocity Impact