HOMOGENIZATION AND MULTISCALE MODELING OF CARBON/CARBON COMPOSITE

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by

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Submitted

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Dedicated to my beloved parents and family.

CERTIFICATE

This is to certify that the thesis entitled "**HOMOGENIZATION AND MULTISCALE MODELING OF CARBON/CARBON COMPOSITE**" being submitted by Mr. **Atul Ramesh Bhagat** 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.

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ABSTRACT

Carbon/Carbon (C/C) composite consists of carbon fiber as reinforcement and carbon as the matrix. The properties of these are governed by the properties of carbon matrix, carbon fiber and interface properties, also the process used for densification. For design and analysis of components made of C/C composites, effective or equivalent homogenized properties of these composites are essential.

Carbon matrix was fabricated and its tensile and shear properties were determined experimentally. Cyclic compression tests were carried out to determine the damage behavior of the carbon matrix, and parameters for damage evolution law to be used in homogenization of the C/C composites were determined.

Stiffness and strength of the interface between fiber and matrix were determined from the transverse tension tests. Tension tests were carried out along the fiber direction for uni-directional (UD) C/C composites. Damage parameters for the carbon fiber bundles were determined from these tests by an iterative process.

Reduced order homogenization method was studied and computer codes were developed for implementation of the scheme to determine the homogenized constitutive law of 3D C/C composites. Properties of the constituents and interface determined earlier were used in the analysis. Properties of the 3D C/C composite were also determined experimentally to validate the model.

The constitutive law developed was used in multiscale analysis of a tension test on plate with a hole and compression test on a hollow cylinder. Experiments were also carried out on these structures and results were compared with the results from simulation.

सार

कार्बन कार्बन (सी / सी) कंपोजिट में कार्बन फाइबर रएंफोर्रसमेंट के रूप में तथा मैट्रिक्स के रूप में कार्बन होते हैं. इनमें से गुणों को कार्बन मैट्रिक्स, कार्बन फाइबर और इंटरफ़ेस गुणों के द्वारा नियंत्रित किया जाता है। कार्बन कार्बन कंपोजिट से घटकों के डिजाइन और विश्लेषण के लिए, कंपोजिट के प्रभावी या समकक्ष समसामयिक गुण आवश्यक हैं।

कार्बन मैट्रिक्स बनाया गया था और इसकी तन्यता और शियर गुण प्रयोगात्मक रूप से निर्धारित किए गए थे । कार्बन मैट्रिक्स के क्षति व्यवहार को निर्धारित करने के लिए चक्रीय संपीड़न परीक्षण किए गए थे और सी / सी कंपोजिट के होमोजनाइजेशन में उपयोग किए जाने वाले क्षति के विकास कानून के लिए पैरामीटर निर्धारित किए गए थे।

फाइबर और मैट्रिक्स के बीच इंटरफ़ेस की कठोरता और ताकत अनुक्रम तनाव परीक्षणों से निर्धारित किए गए थे। यूनिडायरेक्शनल (यूडी) सी / सी कंपोजिट के लिए फाइबर दिशा के साथ तनाव परीक्षण किए गए थे। कार्बन फाइबर बंडलों के लिए क्षति मापदंडों को पुनरावृत्ति प्रक्रिया द्वारा इन परीक्षणों से निर्धारित किया गया था।

3 डी सी / सी कंपोजिट के होमोजीनाइज्ड गठित कानून को निर्धारित करने के लिए और योजना के कार्यान्वयन के लिए रेड्यूसेड आर्डर होमोजिनायझेशन विधि का अध्ययन किया गया और कंप्यूटर कोड विकसित किया गया। पहले परिभाषित घटक और इंटरफ़ेस के गुण विश्लेषण में उपयोग किए गए थे। मॉडल को मान्य करने के लिए 3Dकंपोजिट के गुणों को प्रयोगात्मक रूप से भी निर्धारित किया गया था।

विकसित गठित कानून को एक छेद के साथ प्लेट पर तनाव और एक खोखले सिलेंडर पर संपीड़न परीक्षण के मल्टीस्केल विश्लेषण में उपयोग किया गया था। इन संरचनाओं पर प्रयोग भी किए गए थे और परिणामों की तुलना सिमुलेशन से की गई थी।

TABLE OF CONTENTS

Description of Content **Page No.**

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

$2a, 2b, 2c$	Dimensions of the unit cell, mm
b_1	Width at notch area of Iosipescu test specimen, mm
b	Width of flexural test specimen, mm
d	Height of flexural test specimen , mm
A_a	Projected area of the contact in indentation test
A_{ijkl}	Elastic influence function
A, B, C, D, E, F	Faces of the unit cell
B_i^η	Strain displacement matrix at integration point *i*
$\hat{\mathbf{e}}_p(\hat{\mathbf{y}})$	Unit vector along normal and tangential directions of the fiber bundle in local coordinate system at $\hat{\mathbf{y}}$ location
e_{11}	Macroscopic strain in direction-1
e_{22}	Macroscopic strain in direction-2
e_{33}	Macroscopic strain in direction-3
e_{23}	Macroscopic strain in 2-3 plane
e_{13}	Macroscopic strain in 1-3 plane
e_{12}	Macroscopic strain in 1-2 plane
E, E_1, E_2	Elastic modulus
E_{11}	Young’s modulus in principal material direction -1, GPa
E_{22}	Young’s modulus in principal material direction -2, GPa
E_{33}	Young’s modulus in principal material direction -3, GPa
E_i	Modulus of Berkovich indenter
E_r	Reduced modulus
E_0	Initial Young’s modulus
$\mathbf{f}$	Force term
$\mathbf{f}^{\mathrm{c}}$	Force vector for unilateral contact constrains
f_i^ζ	Body force per unit volume
f_i^η	Force vector at integration point *i* for an element *η*

F	Weighting matrix
ΔF	Change in instantaneous load
F_u	Failure load
F_1	Load in flexural test, N
g_{ijkl}^{ph}	Phase damage influence function
g_{ijm}^{int}	Interface damage influence functions
G	Shear modulus, GPa
G_{12}	Shear modulus in 1-2 plane, GPa
G_{13}	Shear modulus in 1-3 plane, GPa
G_{23}	Shear modulus in 2-3 plane, GPa
h	Penetration depth in indentation tests
h_{im}^{int}	Characteristic function for interface damage
h_{ikl}^{ph}	Characteristic function for phase damage
I_{ijkl}	Fourth order identity tensor
κ_N	Interface stiffness in normal direction , MPa/mm
κ_T	Interface stiffness in tangential direction , MPa/mm
K_{sc}	Stress concentration factor
L_1	Span in flexural test, mm
$\hat{L}$	Tensor of elastic moduli in principal directions of ε^{η}
L^e	Isotropic elasticity tensor
L_{eff}	Effective elastic tensor
L_η	Stiffness matrix of element η.
L_{ijkl}	Tensor of elastic moduli
$N_{\mathrm{ph}}^{(\gamma)}$	Phase shape function
$N_{\mathrm{int}}^{(\beta)}$	Interface shape function
P	Indentation load, N
r, s	Damage evolution constants
$\mathbf{S}$	Interface boundary
S_1	Deflection in flexural test, mm
S_2	Contact stiffness in unloading
$\mathrm{S}^{(\alpha)}$	Interface surface

$\hat{\mathbf{t}}^{(\alpha)}$	Resultant traction on the interface α
t^N	Traction in normal direction
t^T	Traction in circumferential direction
t^a	Traction in axial direction
t	Thickness at notch area of Iosipescu test specimen, mm
u	Displacement at arbitrary point along X direction, mm
v	Displacement at arbitrary point along Y direction, mm
w	Displacement at arbitrary point along Z direction, mm
u_i	Global displacement field
u_i^1	First order displacement field
$\tilde{u}_i$	Damage induced displacement field
$\mathbf{x}$	Macroscale coordinate system
$\mathbf{y}$	Microscale coordinate system
$\hat{\mathbf{y}}$	Location of interface or phase damage
Y	Damage energy release rate
α_{ph} , β_{ph}	Phase damage variables
α_{int} , β_{int}	Interface damage variables
$\Delta\gamma$	Change of shear strain in Iosipescu test
δ_m	Eigen displacement tensor along the interface
$\hat{\boldsymbol{\delta}}^{(\beta)}$	Vector of nodal separations in β interface
$\delta_{\eta\gamma}^{\mathrm{K}}$	kronekor delta function
δ_N	Opening in normal direction
δ_T	Vector consisting displacement jumps in circumferential and axial directions
ε_{ij}^{η}	Non-local strain tensor
$\bar{\varepsilon}_p$	Equivalent plastic strain
$\tilde{\varepsilon}_{kl}$	Damage induced strain tensor
$\bar{\varepsilon}_{kl}$	Average strain tensor
ε_{ij}, ε^e	Strain tensor
ε_{ij}^1	First order strain tensor
$\bar{\varepsilon}_{ij}$	Average strain tensor

ζ	Ratio of size of unit cell and macroscopic domain
Θ	Unit cell
θ_η	Volume of element η
κ	Function of damage equivalent strain
κ_{int}	Function of interface damage equivalent displacement jump
μ_{kl}^{γ}	Eigen strain tensor in γ phase
μ_{kl}	Eigen strain tensor
μ_η	Eigen strain to be applied in element η
υ	Damage equivalent strain
υ_{ini}	Equivalent threshold strain
υ_{int}	Interface damage equivalent displacements
ν_i	Poisson's ratio of the indenter
ν_{12}	Poisson's ration in 1-2 plane
ν_{13}	Poisson's ration in 1-3 plane
ν_{23}	Poisson's ration in 2-3 plane
σ_{ij}	Stress tensor
σ_{ij}^{0}	Zero order stress tensor
σ_{ij}^{1}	First order stress tensor
σ_{ij}^{ζ}	Stress tensor in ζ phase
σ^{∞}	Far field stress component
τ	Shear strength, MPa
$\O$	von Mises yield function
Ω	Macroscopic space
ω	Isotropic damage variable
ω_{ph}	Phase damage variable
ω_{int}	Interface damage variable