STRAIN MEASUREMENTS IN POROUS MATERIALS UNDER COMPRESSIVE LOADS USING DIGITAL VOLUME CORRELATION AND MICRO FINITE ELEMENT MODELING

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by

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submitted
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Dedicated

To my parents and family

Certificate

This is to certify the thesis entitled **"STRAIN MEASUREMENTS IN POROUS MATERIALS UNDER COMPRESSIVE LOADS USING DIGITAL VOLUME CORRELATION AND MICRO FINITE ELEMENT MODELING"** being submitted by Mr. Sriram K is the report of bonafide research work carried by him under our supervision. This thesis has been prepared in conformity with the rules and regulations of the **INDIAN INSTITUTE OF TECHNOLOGY, DELHI.** We further certify that the thesis has attained a standard required for the award of **DOCTOR OF PHILOSOPHY** degree of the institute. The research reported and the results presented in the thesis have not been submitted, in part or full to any other university or institute for any other degree or diploma.

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Abstract

Micro-CT is a non-destructive technique to quantify the morphology of cellular structures. An in-situ testing device and micro-CT enable a qualitative understanding of the microstructural changes due to loading conditions. The quantitative understanding of displacements and strains is obtained by the image-based FE analysis (Micro-FE) of cellular structures. However, the validation of such models is critical due to many influencing parameters.

Digital Volume Correlations (DVC)is an image-based technique to quantify the internal displacements and strains of cellular structures. The technique is also used as a validation tool for micro-FE displacements and strains. Nevertheless, most of these validation has only been performed within the 6-7% strain range. A good comparison between DVC and micro-FE results was obtained when DVC interpolated boundary conditions were implemented. However, the applicability of DVC interpolated boundary conditions in large deformations cases is not studied in detail.

The present study uses DVC and micro-FE techniques to evaluate the internal displacements and strains in closed (CCF) and open (OCF) cell foams under compressive loading conditions. A multi-step compression procedure achieves large deformations (up to 20%) in foams. A local DVC algorithm is implemented to quantify the deformations in the foams. The micro-FE analysis of both foams is performed with DVC interpolated boundary conditions (IPBC) and experiment-based boundary conditions (ExBC). A detailed comparison of the predicted and measured displacements and strains is performed at macroscopic and microscopic levels. An

image-based anisotropy evaluation of foams and the changes in the anisotropy of foams are determined up to 20% strain.

Within the elastic regime, IPBC predicted displacement components showed a good match to the DVC measurements. While ExBC showed a good agreement for transverse displacements only. The statistical analysis of displacement components supported the above mentioned trends in sectional and volume level comparisons. Even though the displacements matched well, the normal strain components were not predicted well.

For large deformation analysis of CCF samples, at volume level comparison, the axial displacement contour was better predicted by ExBC and IPBC, where the correlation values are $R^2 > 0.70$. Even though the ExBC predicted transverse displacement contours differed from DVC, a reasonably well statistical correlation was identified ($R^2 > 0.70$). However, the individual sectional comparison showed a lower correlation ($R^2 < 0.60$), especially for axial displacements predicted by both IPBC and ExBC. For OCF samples, significant differences in the displacement contours predicted by IPBC and ExBC were observed. The statistical comparison showed a variation in the correlation value between $0.04 < R^2 < 0.67$ for transverse displacements, while the axial displacement has a better correlation value range ($0.65 < R^2 < 0.87$). The displacement components failed to correlate well at the sectional level. Even though the measured and predicted strain ranges were similar for both foams, the local strain values differed significantly.All micro-FE results were obtained using the full integration scheme because at large deformations, reduced integration produced a higher artificial energy level (5%>). The deformations of up to 20% strain in both OCF and CCF samples could not significantly alter the anisotropy of the foams. The deformation mechanism predicted by micro-FE using IPBC and ExBC for open and closed-cell foam was similar to that captured by micro-CT in large deformation cases.

The porosity evaluation of Titanium coating was carried out for a sample size of 2 × 4 mm ($\phi \times l$). A combination of smaller sample size and high resolution

imaging was carried out. However, an exact measurement of porosity could not be achieved. This is due to the insufficient scanning parameters.

A CT scan based transversely isotropic inhomogeneous Finite Element model of the femur was developed. The failure probability of the femur bone was determined at the critical yield location, and the sensitivity analysis of the femur identified Young's modulus, shear strength, and the joint contact forces as critical parameters that affect the failure probability of the femur.

संक्षेप

माइक्रो-सीटी सेलुलर संरचनाओं की आकृति विज्ञान की मात्रा निर्धारित करने के लिए एक गैर-विनाशकारी तकनीक है। एक इन-सीटू परीक्षण उपकरण और माइक्रो-सीटी लोडिंग स्थितियों के कारण माइक्रोस्ट्रक्चरल परिवर्तनों की गुणात्मक समझ को सक्षम बनाता है। सेलुलर संरचनाओं के छवि-आधारित FE विश्लेषण (माइक्रो-FE) द्वारा विस्थापन और उपभेदों की मात्रात्मक समझ प्राप्त की जाती है। हालांकि, कई प्रभावशाली मापदंडों के कारण ऐसे मॉडलों का सत्यापन महत्वपूर्ण है।

डिजिटल वॉल्यूम सहसंबंध (डीवीसी) सेलुलर संरचनाओं के आंतरिक विस्थापन और तनाव को मापने के लिए एक छवि-आधारित तकनीक है। तकनीक का उपयोग माइक्रो-एफई विस्थापन और तनाव के लिए एक सत्यापन उपकरण के रूप में भी किया जाता है। फिर भी, इनमें से अधिकतर सत्यापन केवल 6-7% तनाव सीमा के भीतर ही किए गए हैं। डीवीसी और माइक्रो-एफई परिणामों के बीच एक अच्छी तुलना तब प्राप्त हुई जब डीवीसी प्रक्षेपित सीमा शर्तों को लागू किया गया। हालांकि, बड़े विरूपण मामलों में डीवीसी प्रक्षेपित सीमा स्थितियों की प्रयोज्यता का विस्तार से अध्ययन नहीं किया गया है। वर्तमान अध्ययन डीवीसी और माइक्रो-एफई तकनीकों का उपयोग संपीड़ित लोडिंग स्थितियों के तहत बंद (सीसीएफ) और खुले (ओसीएफ) सेल फोम में आंतरिक विस्थापन और तनाव का मूल्यांकन करने के लिए करता है। एक बहु-चरण संपीड़न प्रक्रिया फोम में बड़ी विकृति (20% तक) प्राप्त करती है। फोम में विकृति की मात्रा निर्धारित करने के लिए एक स्थानीय डीवीसी एल्गोरिथ्म लागू किया गया है। दोनों फोमों का माइक्रो-एफई विश्लेषण डीवीसी के साथ किया जाता है प्रक्षेपित सीमा की स्थिति (IPBC) और प्रयोग-आधारित सीमा की स्थिति (ExBC)। मैक्रोस्कोपिक और सूक्ष्म स्तरों पर अनुमानित और मापा विस्थापन और उपभेदों की विस्तृत तुलना की जाती है। फोम के एक छवि-आधारित अनिसोट्रॉपी मूल्यांकन और फोम के अनिसोट्रॉपी में परिवर्तन 20% तनाव तक निर्धारित किए जाते हैं।

लोचदार शासन के भीतर, IPBC ने विस्थापन घटकों की भविष्यवाणी की, DVC मापों के लिए एक अच्छा मेल दिखाया। जबकि एक्सबीसी ने केवल अनुप्रस्थ विस्थापन के लिए एक अच्छा समझौता दिखाया। विस्थापन घटकों के सांख्यिकीय विश्लेषण ने अनुभागीय और मात्रा स्तर की तुलना में उपर्युक्त प्रवृत्तियों का समर्थन किया। भले ही विस्थापन अच्छी तरह से मेल खाता हो, सामान्य तनाव घटकों की अच्छी तरह से भविष्यवाणी नहीं की गई थी।

CCF नमूनों के बड़े विरूपण विश्लेषण के लिए, मात्रा स्तर की तुलना में, अक्षीय विस्थापन समोच्च का ExBC और IPBC द्वारा बेहतर अनुमान लगाया गया था, जहाँ सहसंबंध मान $R^2 > 0.70$ हैं। भले ही एक्सबीसी ने अनुमानित अनुप्रस्थ विस्थापन रूपरेखा डीवीसी से भिन्न थी, एक यथोचित अच्छी तरह से सांख्यिकीय सहसंबंध की पहचान की गई थी ($R^2 > 0.70$)। हालाँकि, व्यक्तिगत अनुभागीय तुलना ने कम सहसंबंध ($R^2 < 0.60$) दिखाया, विशेष रूप से IPBC और ExBC दोनों द्वारा अनुमानित अक्षीय विस्थापन के लिए। OCF नमूनों के लिए, IPBC और ExBC द्वारा अनुमानित विस्थापन रूपरेखाओं में महत्वपूर्ण अंतर देखा गया। सांख्यिकीय तुलना ने अनुप्रस्थ के लिए $0.04 < R^2 < 0.67$ के बीच सहसंबंध मूल्य में भिन्नता दिखाई विस्थापन, जबकि अक्षीय विस्थापन में एक बेहतर सहसंबंध मूल्य सीमा ($0.65 < R^2 < 0.87$) है। विस्थापन घटक अनुभागीय स्तर पर अच्छी तरह से सहसंबद्ध होने में विफल रहे। भले ही मापी गई और अनुमानित स्ट्रेन रेंज दोनों फोम के लिए समान थीं, स्थानीय स्ट्रेन वैल्यू में काफी अंतर था। पूर्ण एकीकरण योजना का उपयोग करके सभी माइक्रो-एफई परिणाम प्राप्त किए गए थे, क्योंकि बड़े विकृतियों पर, कम एकीकरण ने एक उच्च कृत्रिम ऊर्जा स्तर (5%>) का उत्पादन किया। OCF और CCF दोनों नमूनों में

20% तक की विकृति फोम के अनिसोट्रॉपी को महत्वपूर्ण रूप से नहीं बदल सकती है। विरूपण तंत्र सूक्ष्म द्वारा भविष्यवाणी की गई-खुले और बंद-सेल फोम के लिए आईपीबीसी और एक्सबीसी का उपयोग करने वाला एफई बड़े विरूपण मामलों में माइक्रो-सीटी द्वारा कब्जा कर लिया गया था।

टाइटेनियम कोटिंग का सरंध्रता मूल्यांकन 2×4 मिमी के नमूने के आकार के लिए किया गया था। छोटे नमूने के आकार और उच्च रिज़ॉल्यूशन इमेजिंग का संयोजन किया गया। हालाँकि, सरंध्रता का सटीक माप प्राप्त नहीं किया जा सका। यह अपर्याप्त स्कैनिंग पैरामीटर के कारण है।

फीमर का एक सीटी स्कैन आधारित ट्रांसवर्सली आइसोट्रोपिक इनहोमोजेनस फाइनाइट एलिमेंट मॉडल विकसित किया गया था। फीमर हड्डी की विफलता की संभावना महत्वपूर्ण उपज स्थान पर निर्धारित की गई थी, और फीमर के संवेदनशीलता विश्लेषण ने यंग के मापांक, कतरनी ताकत और संयुक्त संपर्क बलों को महत्वपूर्ण मापदंडों के रूप में पहचाना जो फीमर की विफलता की संभावना को प्रभावित करते हैं।

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Nomenclature

Abbreviations

AE	Artificial Energy
CC	Cross Correlation
CCD	Charged Coupled Detector
CCF	Closed Cell Foam
CD	Compression Device
DA	Degree of Anisotropy
DC	Direct Correlations
DIC	Digital Image Correlation
DVC	Digital Volume Correlation
ExBC	Experimental Boundary Conditions
FFT	Fast Fourier Transform
FI	Full Integration
HA	Hydroxyapatite
IE	Internal Energy

IPBC	Interpolated Boundary Conditions
JCF	Joint Contact Force
KE	Kinetic Energy
MAER	Mean Absolute Error
MF	Abductor Muscle Force
micro-CT	Micro-computed tomography
MIL	Mean Intercept Length
MRI	Magnetic Resonance Imaging
MSE	Mean Square Error
NCC	Normalized Cross Correlation
OCF	Open Cell Foam
PU	Polyurethane
RBC	Rigid Body Correction
RBM	Rigid Body Motions
RI	Reduced Integration
SDER	Standard Deviation of Error
SR-micro-CT	Synchrotron-micro computed tomography
SSCC	Sum of Squares Cross Correlation

Greek Symbols

$\bar{\omega}$	Scalar damage variable

$\bar{\sigma}$	Yield stress
δ	Equivalent plastic displacement
δ_{pf}	Equivalent plastic displacement at failure
$\dot{\epsilon}^{p}$	Plastic strain rate
$\dot{\lambda}$	Plastic multiplier
ϵ	Strain
ϵ_e	Elastic strain
ϵ_p	Plastic strain
ϕ	Porosity of foam
ρ^*	Density of foams
ρ^s	Density of the solid material of foam
ρ_{ash}	Ash Density
$\sigma_{ij}^{'}$	Deviatoric components of Cauchy stress
σ_y	Yield stress
θ	Angle of an intercept line for MIL calculations
$\bar{\epsilon}^{p}$	Equivalent plastic strain

Variables

(dx_c, dy_c, dz_c)	Components of corrector vector
(dx_p, dy_p, dz_p)	Components of predictor vector
$\overline{HU}$	Average Hounsfield Unit

$\mathbf{mi}$	Normalized eigenvectors
B	Bulk modulus
C	Viscous coefficients
C^d	Dilatational wave speed
C_{norm}	Normalized Correlation of DVC
D	Deformed image
D_i	Cook's distance
E	Young's modulus
F	Fourier transform
f	Force
F^*	Complex conjugated Fourier transform
F^{-1}	Inverse Fourier transform
G	Shear Modulus
$g(X)$	Probability of performance function
G_f	Fracture energy
H	Second order material tensor
h_m	Hardening modulus
K	Stiffness
K_s	Sensitivity of strain gauge
L	The intercept length between the solid phase change

L_e	Characteristic length of an element
M	Fabric tensor
m	Linear regression slope
M_{coat}	Mass of Coating
M_{sam}	Mass of Sample
$M_{substrate}$	Mass of Substrate
mi	Positive eigenvalues
N	Number of voxels or DVC window size
p	Linear regression intercept
P_f	Probability of failure
Q	Conjugate force developed due to hourglass
R	Reference image
r	Pearson Coefficient
R^2	Coefficient of determination
R_m	Material Resistance
RV	Random Variable
S	Undamaged sectional area
S_D	Damaged sectional area
U, V, W	Displacement components
V	Number of intercept

v_e	Element volume
v_f	Volume fraction of the foam
(dx, dy, dz)	Shift vector components
(x, y, z)	Cartesian co ordinates of voxels