ANALYSIS OF LARGE IN-PLANE DISPLACEMENT AND STRAIN IN RUBBER USING 2-D SCANNER-BASED DIGITAL IMAGE CORRELATION

by

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LIST OF ABBREVIATIONS

2-D	Two-dimensional
3-D	Three-dimensional
2-D DIC	Two-dimensional Digital Image Correlation
2-D SB-DIC	Two-dimensional Scanner Based-Digital Image Correlation
3-D DIC	Three-dimensional Digital Image Correlation
ASTM	American Society for Testing and Materials
CB	Carbon-black
CB-NR	Carbon-black filled natural rubber
CBS	N-cyclohexyl-benzothiazyl-sulphenamide
CC	Cross-correlation
CCD	Charge-coupled device
CCW	Counter-clockwise
CMM	Coordinate measuring machine
CW	Clockwise
DIC	Digital image correlation
DP	Dual-phase
DSLR	Digital Single Lens Reflex
EPDM	Ethylene propylene diene monomer
FEM	Finite element modelling
FOV	Field-of-view
IPPD	N-isopropyl-N'-phenyl-p-phenylenediamine
MATLAB	Matrix laboratory
MDR	Moving die rheometer

MTS	Mesostructural testing system
NCC	Normalized cross-correlation
NR	Natural rubber
PCB	Printed circuit board
PDMS	Polydimethylsiloxane
PHR	Part per Hundred
PIC	Programmable Interface Controller
PR	Poisson’s ratio
ROI	Region of interest
SAD	Sum of absolute differences
SB-DIC	Scanner based-digital image correlation
SEM	Scanning electron microscope
SIF	Stress intensity factor
SMAC	Smactane
SMR L	Standard Malaysia Rubber L-grade
SSD	Sum-squared difference
SSSIG	Sum of Square of Subset Intensity Gradients
TiAl	Titanium alloy
UK	United Kingdom
uNR	Unfilled natural rubber
USA	United States of America
USC	University of South Carolina
ZNCC	Zero-Mean normalized cross correlation

LIST OF SYMBOLS

a	Constant in polynomial equation
$\mathbf{a}$	Vector in reference subset
α_i	Material constant
B	Initial value in decay function
A	Cross sectional area
b	Constant in polynomial equation
$\mathbf{b}$	Vector in deformed subset
$B1$	Marker 3
$B2$	Marker 4
c	Constant in polynomial equation
C_1	Material constant
C_2	Material constant
C_3	Material constant
C_4	Material constant
C_5	Material constant
d	Constant in polynomial equation
Δl	Elongation
Δw	Width contraction
d_{pixel}	Distance in pixel unit
ε_a^e	Engineering axial strain
ε_l^e	Engineering lateral strain in width
$\varepsilon_{resultant,DIC}^e$	Resultant strains in 2-D DIC method
$\varepsilon_{resultant,FEM}^e$	Resultant strains in FEM

ε_a^t	True axial strain
ε_l^t	True lateral strain in width
ε_{lt}^e	Engineering lateral strain in thickness
f	Subset centred at reference image
$f(x_i, y_j)$	Pixel value in the reference image
F	Force applied or load applied on rubber specimen in UTM
F_a	Downward force
F_h	Force applied on handle
F_{nr}	Restoring forces in the rubber specimen after applying correction factor
F_{out}	Output force
F_r	Restoring forces in the rubber specimen before applying correction factor
F_s	Restoring forces in the springs
$\mathbf{F}$	2-D deformation factor
g	Subset centred at deformed image
g_r	Gear ratio
$g(x'_i, y'_j)$	Pixel value in the deformed image
γ_1	Shear strain in *x*-direction on *yz*-plane
γ_2	Shear strain in *z*-direction on *yz*-plane
γ_3	Shear strain in *z*-direction on *xz*-plane
$\hat{\imath}$	Component vector in horizontal direction
I_1	First invariant
I_2	Second invariant
I_3	Third invariant

$\hat{j}$	Component vector in vertical direction
k	Spring constant
$k_{eq.}$	Equivalent spring constant
k_{out}	Spring constant of the output spring
λ_1	Axial stretch ratio or elongation deformation factor
λ_1'	Axial stretch ratio or elongation deformation factor at particular point
λ_2	Lateral contraction ratio in width or lateral deformation factor
λ_2'	Lateral contraction ratio or lateral deformation factor in width at particular point
λ_3	Lateral contraction ratio in thickness
l	Pitch of the leadscrew
l_f	Final gauge length
l_i	Initial gauge length
l_{fs}	Final length given by the distance of the centroid of each subset from the reference end
l_{is}	Initial length given by the distance of the centroid of each subset from the reference end
m	Subset row
μ_i	Material constant
n	Subset column
r	Radius
R_0	Decay rate
$R_{corrected}$	Corrected scanning resolution
$\bar{R}_{corrected}$	Mean corrected scanning resolution
s	Displacement

$\bar{s}$	Average displacement
$S1$	Marker 1
$S2$	Marker 2
σ	Engineering stress
σ'	Engineering stress at particular point
t_c	Programme code running time
t_l	Loading process time
t_s	Scanning process time
$\bar{T}$	Mean thickness
T_h	Binarization threshold value before auto-cropping process
T_s	Binarization threshold value after auto-cropping process
τ_{i}	Input torque
τ_{o}	Output torque
v	variable used to keep tracking of the number of images read
v^e	Poisson's ratio based on engineering strain
$v^{e\prime}$	Poisson' ratio based on engineering strain at particular point
v^t	Poisson's ratio based on true strain
w_{is}	Initial width given by the distance between center points of each subset from the center position
w_{fs}	Final width given by the distance between center points of each subset from the center position
W	Function of the strain invariants or principle stretch ratios
$\bar{W}$	Mean width
W_r	Maximum load to be applied onto the rubber specimen
x	Variable in decay function

x_o	Length in horizontal direction in reference subset
x'	Length in horizontal direction in deformed reference subset
$x_{avg.}$	Average extension of springs
x_{out}	Extension for the output spring
y_{off}	Offset from the *x*-axis in decay function
y_o	Length in vertical direction in reference subset
y'	Length in vertical direction in deformed reference subset
y_1	*y*-coordinates of the top left corner in marker *B1*
y_2	*y*-coordinates of the bottom left corner in marker *B2*

ANALISA ANJAKAN SATAH YANG BESAR DAN TERIKAN BAGI GETAH MENGGUNAKAN KORELASI IMEJ DIGITAL BERASASKAN PENGIMBAS 2-D

ABSTRAK

Pelbagai teknik korelasi imej digital (DIC) telah diperkenalkan pada masa lalu untuk menyelesaikan masalah medan penglihatan (FOV) yang terhad untuk ukuran defomasi yang besar. Walau bagaimanapun, kaedah-kaedah tersebut berkongsi satu kelemahan iaitu FOV yang rendah. Dalam penyelidikan ini, satu kaedah yang baru iaitu korelasi imej digital dua dimensi berasaskan pengimbas (2-D SB-DIC) yang memberikan FOV yang besar untuk pengukuran deformasi yang besar bagi specimen getah asli (uNR) yang tidak diisi telah dibangunkan. Untuk mendapatkan data bagi anjakan, terikan, beban dan tekanan, imej-imej telah diimbas dan diproses. Data anjakan diperolehi dengan menggunakan algoritma korelasi imej meningkat. Min untuk modulus tangen and modulus sekan bagi specimen uNR yang diperolehi daripada kaedah 2-D SB-DIC dari lima eksperimen berulang telah dibandingkan dengan hasilan yang diperolehi daripada mesin ujian sejagat (UTM). Satu algoritma baru untuk pemetaan deformasi yang besar bagi specimen uNR dalam satu langkah tanpa memerlukan siri deformasi imej juga dibangunkan. Terikan paksi yang diperolehi daripada cadangan algoritma langkah tunggal 2-D SB-DIC telah dibanding dengan hasilan yang diperolehi daripada algoritma konvensional meningkat korelasi imej digital. Ujian-ujian agihan terikan yang tidak homogen juga telah dijalankan dengan menganalisa deformasi bagi dua specimen getah bersegi empat yang mengandungi lubang bulat dan segi empat tepat dengan menggunakan algoritma yang dicadangkan. Peta-peta terikan paduan bagi spesimen getah segi

empat tepat dibandingkan dengan hasilan yang diperolehi daripada model unsur terhingga (FEM). Modulus Young yang diperoleh dengan menggunakan algoritma mengingkat 2-D SB-DIC menunjukkan maksimum kesilapan mutlak sebanyak 9.5% pada 250% terikan paksi dan 4.2% pada 50% terikan paksi bagi modulus tangen and modulus sekan, masing-masing. Sementara itu sisihan maksimum nisbah Poisson berdasarkan terikan kejuruteraan dan terikan sebenar sehingga nilai ambang bagi ketakbolehmampatan untuk bahan polimer adalah hanya 1.36% dan 1.24%, masing-masing. Maksimum sisihan mutlak sebanyak 10.7% pada terikan paksi 320% telah didapati dengan menggunakan cadangan algoritma langkah tunggal 2-D SB-DIC. Untuk ujian-ujian agihan terikan tidak homogen, perbandingan hasilan peta terikan menunjukkan bahawa cadangan algoritma langkah tunggal berganding dengan kaedah 2-D SB-DIC boleh digunakan untuk pemetaan terikan dengan tepat bagi bahan deformasi yang besar seperti getah. Algoritma 2-D DIC langkah tunggal menghapuskan ralat kumulatif yang diperkenalkan daripada algoritma 2-D DIC meningkat di samping mengurangkan masa pemprosesan dalam pemerolehan imej dan imej korelasi dengan banyak.

ANALYSIS OF LARGE IN-PLANE DISPLACEMENT AND STRAIN IN RUBBER USING 2-D SCANNER-BASED DIGITAL IMAGE CORRELATION

ABSTRACT

Various digital image correlation (DIC) techniques have been introduced in the past to solve the limited field-of view (FOV) problem for large deformation measurement. However, these methods share a common limitation which is low FOV. In this research, a novel two-dimensional scanner-based digital image correlation (2-D SB-DIC) method that enables the acquisition of a large FOV of an unfilled natural rubber (uNR) specimen at large deformation has been developed. The images were scanned and processed to obtain displacement, strain, load and stress data. The displacement data were obtained by using the incremental image correlation algorithm. The mean of the tangent and secant moduli of the uNR specimen obtained from the 2-D SB-DIC method from five repeated experiments were compared with those obtained from a universal testing machine (UTM). A new algorithm for mapping large deformation in the uNR specimens in a single-step without the need for a series of deformation images has also been developed. The axial strains obtained by using the proposed single-step 2-D SB-DIC algorithm were compared with those obtained using the conventional incremental image correlation algorithm. Non-homogeneous strain distribution tests were also conducted by analysing the deformation of two rectangular rubber specimens containing circular and square holes using the single-step 2-D SB-DIC algorithm. The resultant strain maps for the rectangular specimens were compared with those from finite element modelling (FEM). The Young's moduli obtained by using the incremental 2-D SB-DIC