2019 iDICs CONFERENCE

OCTOBER 14–17, 2019 | PORTLAND, OR USA

iDICs Conference and Workshop

DOUBLETREE BY HILTON PORTLAND

iDICs INTERNATIONAL DIGITAL IMAGE CORRELATION SOCIETY

MISSION: EXTEND – IMPROVE – TRAIN

Extending the Frontiers: Training the next Generation:
Standardizing for Industry: Improving our Practice

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correlated SOLUTIONS

We continue to develop new and innovative solutions for complex testing applications.
Visit us at booth #17-18 to explore all the ways that Correlated Solutions can improve your research.

VIC-3D 9

Non-Contact Full-Field 3D Strain Measurement System

In 2020, version 9 of our flagship VIC-3D system (code name 'Iris') will be released with a range of groundbreaking new features to improve the validation of theoretical data from testing data. With much more user control of information, 'Iris' will produce publication-ready plots with scalable fonts, editable labels, and high resolution isoline renderings using a new animation and graphics engine. Later in 2020, VIC-3D will also allow for the importation of finite element data which will streamline the product validation process and improve overall efficiency. Visit our booth for more information.

VIC-EDU

Now with all new lab materials

The VIC-EDU system is a low-cost solution developed for academic institutions to assist in teaching the digital image correlation technique to undergraduate and graduate students. The VIC-EDU system utilizes the same accurate algorithms as VIC-3D with streamlined acquisition, calibration, and post-processing capabilities.

Using the QR code here, please visit our website to view our complete product line of digital image correlation systems.

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CONTENTS

Plenary: iDICs Committee Updates

Updates and overview—Tuesday, October 15 | 9:00 a.m. | Mt. Helens/Mt. Hood

The committees will be meeting Tuesday, October 15 after lunch. The committees are open to all attendees, and everyone is encouraged to participate in as many committees as they would like. Each committee's activities are briefly described below, and there will be an update on each presented during the morning plenary at 9 a.m. on Tuesday, October 15.

Standardization, Good Practices, and Uncertainty Quantification Committee

Tuesday, October 15 | 1:00 p.m. | Mt. Hood

Chair: Mark Iadicola and Elizabeth Jones

- Good Practices Guide for DIC idics.org/guide
- Developing other good practice guidelines and terminology unification
- Promoting standardization of DIC
- DIC Challenge (2D, Stereo, DVC, SEM) sem.org/dicchallenge
- Uncertainty quantification for DIC

Education Committee

Tuesday, October 15 | 1:00 p.m. | Mt. Helens

Chair: Mark Pankow and Brian Bay

- Creation and continuing advancement of educational material for DIC
- Teaching methods/techniques/tools outside of the certification framework
- Short courses at the iDICs annual meeting
- Workshops or short courses at other venues or meetings

Training and Certification Committee

Tuesday, October 15 | 3:30 p.m. | Mt. Hood

Chair: Tim Schmidt and Phillip Reu

- Sets the content for each level of iDICs certification
- Organizes certification examinations
- Implementation of certification training

Applications Committee

Tuesday, October 15 | 3:30 p.m. | Mt. Helens

Chair: Alessandro Vieira and David Dawicke

- Organizes the sessions at iDICs annual meeting
- Typical applications (2D, Stereo, Volumetric,...)
- Advanced applications (including new horizons of the technique)
- Industrial applications
- Select papers for invitation for publication

2019 Founders Award

Plenary and Recipients—Wednesday, October 16 | 9:00 a.m. | Mt. Helens/Mt. Hood

Kyung-Suk Kim

Plenary

DIC at a Small World of Nano Science and Technology

The first subject to be reviewed will be the pioneering work of G. Vendroux and W. G. Knauss on nanoscale digital image correlation (DIC) with scanning tunneling microscope, published as a series of three papers in Experimental Mechanics in 1998. Following the review, discussed will be recent and potential issues in applications of DIC in nano and/or soft-material science and technology. At the nanoscale, a variety of scanning probe microscopy are widely employed for DIC analysis; however, scanning distortions have to be rectified by precise periodicity of standard reference lattices of highly stable atomic structures such as graphene. To this end, a dual-tip scanning probe microscopy associated with spectral DIC will be introduced. As an example of DIC application in nanoscale soft-material science and technology, DIC analysis with tapping-mode AFM scanning will be deliberated. The tapping mode AFM DIC is used for a study of nanoscale deformation mechanisms responsible for ultra-high-strength behavior of nano-dispersed copolymers, such as polyurea, exhibited at high strain rates.

Biography

Kyung-Suk Kim has 39 years of experience as an engineering science faculty and is currently Professor of Engineering at Brown University. He received his Ph.D. (1980) in Solid Mechanics from Brown University, and did postdoc in Aeronautics at Caltech (1979-80). He taught at TAM Department, University of Illinois, Urbana-Champaign for 9 years until he joined Brown as Professor of Engineering in 1989. He served as a board member (2012-2015) and the Representative of the Society of Engineering Science (SES) to U.S. National Committee for Theoretical and Applied Mechanics (2016-2018). He recently worked as the Director of the Center for Advanced Materials Research at Brown for five years (2014-19). His research interests are in scale-bridging mechanics, and nano and micromechanics of solids. Through his research on dynamic properties of solids, adhesion and friction, ruga mechanics of soft materials and stability of nanostructures, he has invented numerous new scientific instruments, including various interferometers and image-analysis tools, and analytical methods. He has advised more than 40 Ph.D. students and postdocs. He has received various awards including the Melville Medal (1981) and the Drucker Medal from ASME (2016), the John Simon Guggenheim Fellowship (1996), the Ho-Am Prize in Engineering (2005), and the Engineering Science Medal from the Society of Engineering Science (2012). His research on "New Math for Designer Wrinkles" was selected as one (# 30) of the Top 100 Science Stories, in Discover (2015). He also gave the prestige lecture of the Society for Experimental Mechanics, William M. Murray Lecture (2019).

Recipients

Prof. Wolfgang Knauss and Dr. Guillaume Vendroux

The Founder's Award within the International Digital Image Correlation Society (iDICs) is awarded to individuals who have made a pioneering contribution, either through a novel application of image correlation or development of methodologies that have significantly impacted the field. The Founder's Award recipients for 2019 are Prof. Wolfgang Knauss and Dr. Guillaume Vendroux.

Wolfgang Knauss

Guillaume Vendroux

Published in three tightly coupled papers in Experimental Mechanics in 1998, their research studies included (a) construction of a novel high magnification scanning tunneling electron microscope (STEM) imaging system, (b) modification of image correlation algorithms to analyze the STEM images and (c) demonstration of the capabilities of the STEM system with image correlation to obtain deformation measurements. The work of the authors was so unique that it was more than a decade ahead of future image correlation applications using scanning electron microscope (SEM) images. In fact, publication of their contributions was exceedingly difficult due to the lack of reviewers with sufficient background to assess the breadth and depth of their contributions.

Not only did the recipients construct a fully functional STEM system, but they also showed that the gradient algorithms used in image correlation matching could be simplified to speed up analyses without affecting accuracy of the results. Even today, over 20 years after their unique contributions were published, their first-ever studies remain a shining example of what motivated, outstanding investigators can achieve.

Plenary: Recent DIC Activities at NASA Langley Research Center

Dr. David Dawicke—Thursday, October 17 | 9:00 a.m. | Mt. Helens/Mt. Hood

David Dawicke

Plenary

Recent DIC Activities at NASA Langley Research Center

The NASA Langley Research Center has been an active user of digital image correlation (DIC) for materials and structural testing going back to the 1990's. The DIC measurements are made for model/test correlation; understanding of failure mechanisms, material behavior, and structural response; and qualification of flight hardware. This presentation will provide an overview of projects that have used DIC as a primary measurement technique during the past two years. The projects to be presented will include:

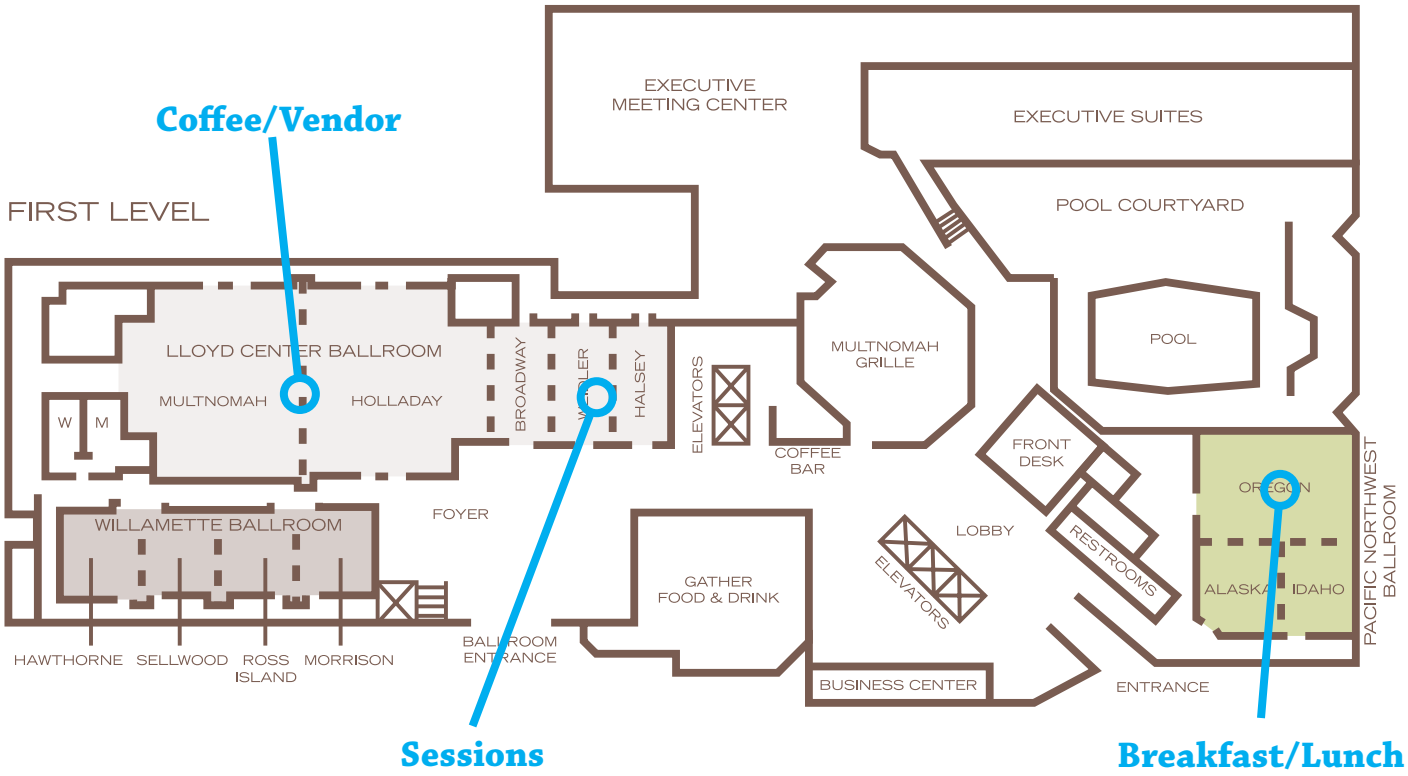
- Ultra-high speed testing of frangible joints for the separation of space vehicle stages for structural understanding and model/test correlation
- Large scale testing of a tailored composite wing
- Large scale testing of composite cylindrical cylinders that represent launch vehicle external tanks
- Large scale testing of the Mars 2020 heat shield for flight qualification
- Testing of composite stiffened panels for damage progression measurements
- Small scale testing of aluminum coupons to examine the influence of grain structure on strain localization
- Small scale testing of aluminum, titanium, and Inconel coupons to examine crack growth behavior

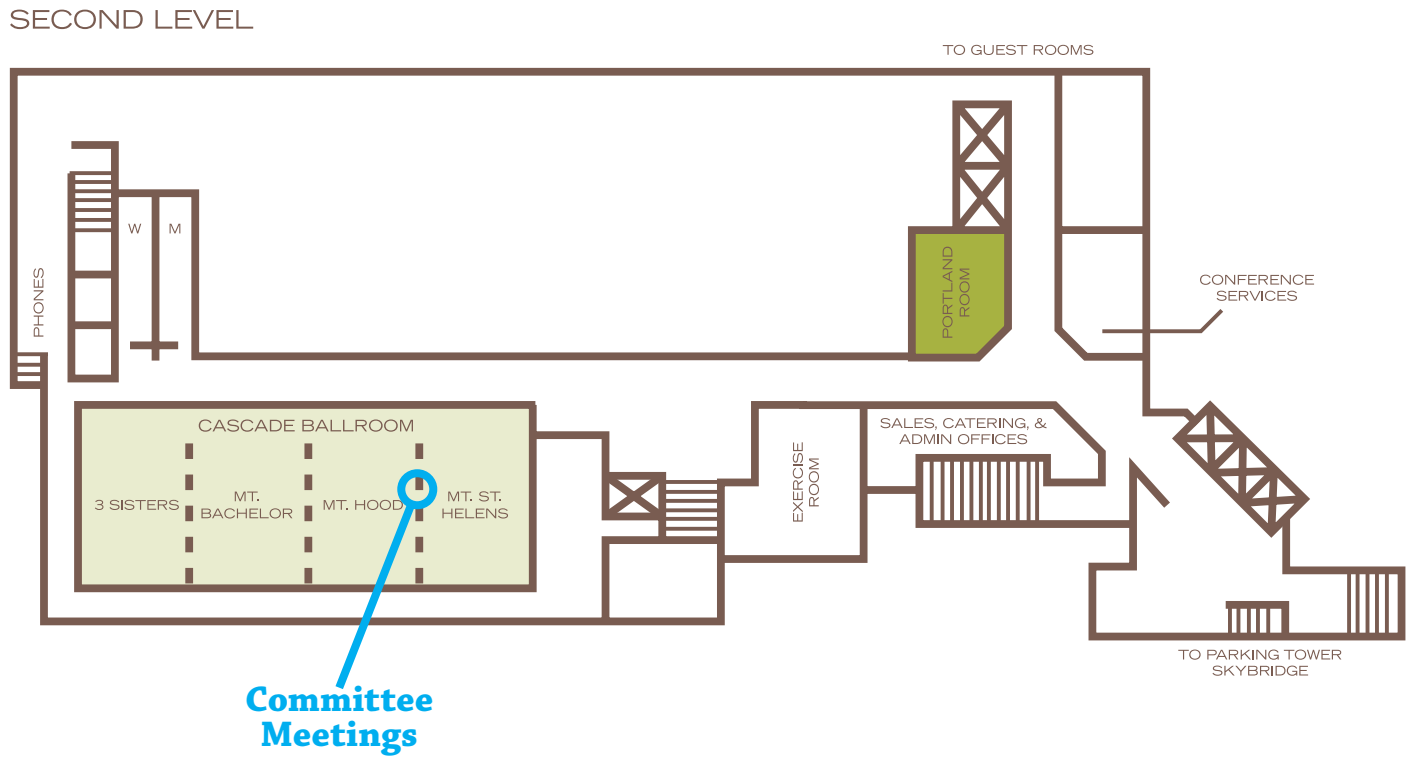
The presentation will present case studies that describe the requirements and challenges of each test, the DIC solution, and a summary of the results and findings.

Biography

Dr. Dawicke has received a Ph.D. from Purdue University and a M.S.M.E and B.S.M.E. from the University of Dayton. Currently, Dr. Dawicke is a Senior Scientist at Analytical Services and Materials, Inc. He has been conducting experimental and analytical fatigue and fracture research at the NASA Langley Research Center since 1986. He has been using 3D digital image correlation for more than 10 years and has characterized the structural response and failure behavior in tests that ranged from 0.03 inch carbon fiber bundles to 30 ft. long composite wing boxes and at test durations that ranged from weeks to microseconds.

DoubleTree by Hilton Portland Floorplan





At-a-Glance Schedule

Time	MONDAY, OCT. 14, 2019	TUESDAY, OCT. 15, 2019	WEDNESDAY, OCT. 16, 2019	THURSDAY, OCT. 17, 2019
7:30 a.m.		Breakfast Buffet until 8:45 a.m. [PNW Ballroom]	Breakfast Buffet until 8:45 a.m. [PNW Ballroom]	Breakfast Buffet until 8:45 a.m. [PNW Ballroom]
8:30 a.m.				
9:00 a.m.	**Morning Courses** DIC 101: Practical Considerations for Good DIC Measurements [Mt. Hood]	Plenary: iDICs Committee Updates [Mt. Hood/Helens]	Wolfgang Knauss Founders Award Plenary: Kyung-Suk Kim [Mt. Hood/Helens]	Plenary: Dr. David Dawicke [Mt. Hood/Helens]
10:00 a.m.		Morning Coffee Break/Vendor	Morning Coffee Break/Vendor	Morning Coffee Break/Vendor
10:40 a.m.	Patterning for DIC: How to pattern everything! [Mt. St. Helens]	**3 Parallel Sessions** UQ 1 [Broadway] Industrial 1 [Weidler] Civil [Halsey]	**3 Parallel Sessions** UQ 2 [Broadway] Industrial 2 [Weidler] Material 1 [Halsey]	**3 Parallel Sessions** High Speed 1 [Broadway] Bio 1 [Weidler] Material 4 [Halsey]
11:00 a.m.				
11:20 a.m.				
11:40 a.m.				
12:00 p.m.	Lunch	Lunch Buffet (1 hr)	Lunch Buffet (1hr)	Lunch Buffet (1 hr)
1:00 p.m.	**Afternoon Courses** DIC 201: Advanced DIC Concepts and Uncertainty Quantification [Mt. Hood]	**Committee Meetings (2 hrs)** Standards [Mt Hood] Education [Mt. St. Helens]	**3 Parallel Sessions** Modal DIC 1 [Broadway] Algorithms 1 [Weidler] Automotive [Halsey]	**3 Parallel Sessions** High Speed 2 [Broadway] Bio 2 [Weidler] Material 5 [Halsey]
1:20 p.m.				
1:40 p.m.				
2:00 p.m.				
2:20 p.m.	The Grid Method: Principles, Performance, and Tutorial [Mt. St. Helens]		Afternoon Coffee Break/Vendor	Afternoon Coffee Break
3:00 p.m.		Afternoon Coffee Break/Vendor	**3 Parallel Sessions** Modal DIC 2 [Broadway] Algorithms 2 [Weidler] Material 2 [Halsey]	**2 Parallel Sessions** Volumetric [Broadway] Petroleum [Halsey]
3:20 p.m.		**Committee Meetings (2 hrs)** Certification [Mt Hood] Applications [Mt. St. Helens]		
3:40 p.m.				
4:00 p.m.				
4:20 p.m.			Afternoon Snack/Vendor	**End of Conference**
4:40 p.m.			**3 Parallel Sessions** Modal DIC 3 [Broadway] Model Validation [Weidler] Material 3 [Halsey]	
5:00 p.m.	Mandatory Vendor Meeting			
5:20 p.m.				
5:40 p.m.		**iDICs City Tour and Correlated Solutions Pub Night** [Meet in the Hotel Lobby]		
6:30 p.m.			DIC Challenge [Broadway]	
7:00 p.m.	**GOM/Trilion President's Reception [Oregon]**			
7:30 p.m.			Dinner on your own	
9:00 p.m.				

Detailed Schedule

	BROADWAY	WEIDLER	HALSEY
Tuesday Morning October 15, 2019	**UNCERTAINTY QUANTIFICATION 1** *Chair(s):* **Mark Iadicola**	**INDUSTRIAL 1** *Chair(s):* **Alessandro Vieira**	**CIVIL** *Chair(s):* **Devin Harris and Xiao-Wei Ye**
7:30 a.m.	**Breakfast Buffet until 8:45 a.m.**—Pacific Northwest Ballroom		
9:00 a.m.	**Plenary: iDICs Committee Updates**—Mt. Hood/Helens		
10:00 a.m.	**Coffee Break in Vendor Exposition**—Multnomah/Holladay		
10:40 a.m.	Acceptance and Verification of DIC Systems with Reference to VDI/VDE Guidelines **Witzel, Oliver**	Utilizing Three-Dimensional Digital Image Correlation (3-D DIC) on Space Flight Hardware **Gardner, Nathaniel**	Full-Field Correlated Mechanics of Cross-Laminated Timber **Buck, Dietrich**
11:00 a.m.	VDI 2626: Directive and hybrid calibration method, implemented and used in VIC **Schreier, Hubert**	Dynamic Deformation of Cover Glass in Mock Phone for Different Orientations of Drop **Singh, Charandeep**	Mixed Finite Element-DIC Technique to Detect Unseen Abnormalities of a Structure Using an Inverse Approach **Harris, Devin**
11:20 a.m.	Development of Laboratory Experiments Utilizing StereoDIC for Accurate Measurement of In-Plane and Out-of-Plane Deformations **Sutton, Michael**	Leveraging Emerging Technology at the Speed of Change in Human Space Flight **Shannon, Ryan**	Evaluation of The Cement Bond Integrity by Using Digital Image Correlation (DIC) Technique **Wu, Yuxing**
11:40 a.m.	Design and Application of a Reference Standard for the Calibration of Full-field Optical Strain Measurements in Full-scale Test Applications **Backman, David**	An overview of DIC technology applications at Boeing **Vieira, Alessandro**	Performance Evaluation of Three-Tab Shingles With Dual Sealant Strips Subjected to Wind Gusts Up To 150 Mph Using Stereo Digital Image Correlation **Rajan Kattil, Sreehari**
12:00 p.m.	**Lunch**—Pacific Northwest Ballroom		
Tuesday Afternoon October 15, 2019	**COMMITTEE: STANDARDS & GOOD PRACTICES** *Chair(s):* **Mark Iadicola**	**COMMITTEE: EDUCATION** *Chair(s):* **Mark Pankow**	
1:00 p.m.	**IN MT. HOOD**	**IN MT. ST. HELENS**	
3:00 p.m.	**Coffee Break in Vendor Exposition**—Multnomah/Holladay		
Tuesday Late Afternoon October 15, 2019	**COMMITTEE: TRAINING & CERTIFICATION** *Chair(s):* **Tim Schmidt**	**COMMITTEE: APPLICATIONS** *Chair(s):* **Alessandro Vieira**	
3:30 p.m.	**IN MT. HOOD**	**IN MT. ST. HELENS**	
5:40 p.m.	**iDICs City Tour and Correlated Solutions Pub Night**—Hotel Lobby		

Detailed Schedule

	BROADWAY	WEIDLER	HALSEY
Wednesday Morning October 16, 2019	UNCERTAINTY QUANTIFICATION 2 *Chair(s):* **Phillip Reu**	INDUSTRIAL 2 *Chair(s):* **Alessandro Vieira**	MATERIAL 1 *Chair(s):* **David Dawicke**
7:30 a.m.	**Breakfast Buffet until 8:45 a.m.**—Pacific Northwest Ballroom		
9:00 a.m.	**Wolfgang Knauss Founders Award Plenary: Kyung-Suk Kim**—Mt. Hood/Helens		
10:00 a.m.	**Coffee Break in Vendor Exposition**—Multnomah/Holladay		
10:40 a.m.	On the Pattern Induced Bias in DIC **Blaysat, Benoit**	Application of a Three-Dimensional Digital Image Correlation for Measurement of Clad Tube Deformation under Transient Heating and Pressurization **Kim, Dong-Hyun**	DIC Analysis to Investigate the Post-Overload Fatigue Crack Growth Behavior **Gonzales, Giancarlo**
11:00 a.m.	Minimizing Pattern Induced Bias in Digital Image Correlation **Fayad, Samuel**	3D Micro Stereo Sensor for Digital Image Correlation **Pulju, Hendrik**	A Model-Free Analysis of Small Scale Yielding to Generalized Plasticity Transition during Mixed-Mode Fatigue Crack Propagation **Langlois, Raphaël**
11:20 a.m.	New Method for DIC Uncertainty Quantification in Industrial Environments **Siebert, Thorsten**	Comprehensive Layer Monitoring during Selective Laser Melting with Stereo-DIC Powder Surface Profiling **Bay, Brian**	Determining Fracture Toughness of Composite Joints: A New Matlab Software and Methods Comparison **Caltagirone, Peter**
11:40 a.m.	Experimental Configuration Calculator for 3-D Image Correlation **McNeill, Stephen**	Fluid Mechanics Application of DIC: Liquid Sloshing **Chao, Bill Yuh**	Effect of Adhesive Thickness and Strain Rate on Mode I Fracture Toughness of Polymer Modified Bitumen - An Experimental Investigation Using StereoDIC **Rajan Kattil, Sreehari**
12:00 p.m.	**Lunch**—Pacific Northwest Ballroom		
Wednesday Afternoon October 16, 2019	MODAL DIC 1 *Chair(s):* **Christopher Niezrecki**	ALGORITHMS 1 *Chair(s):* **Pascal Lava**	AUTOMOTIVE *Chair(s):* **Mark Iadicola**
1:00 p.m.	Application of Stereo 3D Digital Image Correlation in Mach 2, 4, and 6 Wind-tunnels **Ehrhardt, David**	DICe: An Open Source DIC Platform for DIC-related Research **Turner, Daniel**	Characterization of Sheet Formability using Hydraulic Bulge Tests with DIC **Song, Yang**
1:20 p.m.	ODS Detection in Modern DIC Software Environment **Weikert, Thorsten**	Digital Image Correlation: Practical Implementation of a 2D Digital Image Correlation Framework as a MATLAB Code **Atkinson, Devan**	Determination of the Forming Limit Curve and Bi-Axial Yield Curve using Digital Image Correlation up to 1200°C **Grube, André**
1:40 p.m.	Vibration Modes Measurement of a Thin Plate using Single High Speed Camera with FE Model **Liang, Zhonghan**	The Utility of Open Source 2D-DIC Engine Ncorr for Large Compressional Inhomogeneous Deformations in Solid Mechanics **Xing, Xiao Cheng**	Sheet Metal Formability Characterization under Hot Stamping Conditions **DiCecco, Sante**
2:00 p.m.	Vibration Based Stitching Technique to Obtain Deflection Shapes using DIC **Baqersad, Javad**	Robust Heuristics-Enabled, Vision-Based Sensing for Road Traffic Artifacts **Manimala, James**	Combination of Scans and Measured 3D Data for the Calculation of Virtual Geometry Elements **Acun, Burak**

Detailed Schedule

	BROADWAY	WEIDLER	HALSEY
Wednesday Late Afternoon October 16, 2019	MODAL DIC 2 *Chair(s):* **Timothy Beberniss**	ALGORITHMS 2 *Chair(s):* **Elizabeth Jones**	MATERIAL 2 *Chair(s):* **Dan Turner**
2:20 p.m.	**Coffee Break in Vendor Exposition**—Multnomah/Holladay		
3:00 p.m.	An Approach for Dynamic Model Calibration Using Error Localization Algorithms: Demonstration Using Two Practical Examples **Horta, Lucas**	Studying Feasibility of Applying Digital Image Correlation Algorithms on Infrared Images **Pappalettera, Giovanni**	Quantifying Surface Deformation around Small-Scale Indents by Digital Image Correlation **Liu, Mengying**
3:20 p.m.	Eliminating Mass Effects of Multi-transducers in Vibration Test **Zhu, Rui**	Using Finite Elements as a Means to Interpolate and Extrapolate Local Mechanical Fields from Discrete Experimental Data **Roucou, David**	In-Situ Full Field out of Plane Displacement and Strain Measurements at the Micro-Scale in Single Reinforcement Composites under Transverse Loading **Tabiai, Ilyass**
3:40 p.m.	Damper Experimental and Numerical Correlation **Cook, Jason**	The Virtual Image Correlation Method: Principle and Uncertainty **Francois, Marc**	Concurrent, in Situ HR EBSD and DIC on a Three-point Bend IN718 Specimen **Hochhalter, Jacob**
4:00 p.m.		Discontinuity detection using pixel-wise DIC **Couty, Victor**	Nanoimprint Lithography Speckle Patterns for Optical Microscopy DIC **Kursun, Elif Cansu**
4:20 p.m.	**Coffee Break in Vendor Exposition**—Multnomah/Holladay		
Wednesday Evening October 16, 2019	MODAL DIC 3 *Chair(s):* **Javad Baqersad**	MODEL VALIDATION *Chair(s):* **Jean-Noël Périé**	MATERIAL 3 *Chair(s):* **Julien Réthoré**
4:40 p.m.	Validation Testing of DIC Frequency Domain Tools for Modal Analysis **Schmidt, Tim**	DIC and Digital Twin: An Inescapable Combo for an Efficient Model Validation **Swiergiel, Nicolas**	Simultaneous IR/DIC Measurements for Thermomechanical Modeling **Jones, Amanda**
5:00 p.m.	Investigation of Bolt Loosening in Super-alloy Thermal Protection System Panel using High-speed Digital Image Correlation **Goo, Nam Seo**	Benefits of Virtual Testing for Test Validation with Blender **Baudoin, Pierre**	Investigation of Fluid-Structure Interactions in a Shock Tube Using Digital Image Correlation **Jones, Elizabeth**
5:20 p.m.		DIC Uncertainty Quantification in Practice **Lava, Pascal**	Elevated Temperature Optical Microscopy DIC **Connolly, Kevin**
5:40 p.m.			A New DIC-based Test Method for Characterizing Void Formation in Uncured Autoclave Prepregs **Seon, Guillaume**
6:30 p.m.	DIC CHALLENGE MEETING		

Detailed Schedule

	BROADWAY	WEIDLER	HALSEY
Thursday Morning October 17, 2019	**HIGH SPEED 1** *Chair(s):* **Phillip Jannotti**	**BIO 1** *Chair(s):* **Paul Moy**	**MATERIAL 4** *Chair(s):* **Pascal Lava**
7:30 a.m.	**Breakfast Buffet until 8:45 a.m.**—Pacific Northwest Ballroom		
9:00 a.m.	**Plenary: Dr. David Dawicke**—Mt. Hood/Helens		
10:00 a.m.	**Coffee Break**—Multnomah/Holladay		
10:40 a.m.	The Crack-wave Interaction Mechanism in Defected Material Under Impact Loads **Guo, Yang**	3D DIC Evaluation of Musculoskeletal Soft Tissue: Advantages and Challenges **Hooke, Alexander**	A New Approach to Experimental Fracture Analysis of High-toughness Films **Furmanski, Jevan**
11:00 a.m.	Application of High-Speed Digital Image Correlation to Taylor Impact Testing **Jannotti, Phillip**	Portable DIC for Dolphin Skin in-Vivo Measurement under Vacuum Loading **Yang, Dory**	Optimized Stereo Digital Image Correlation Setup for Miniature Round Specimen **Rahman, Farhan**
11:20 a.m.	Enhanced Digital Image Correlation with Enforced Traction Continuity Across Interfaces **Tal, Yuval**	Digital Image Correlation Analysis of Dental Implant Insertion **Yang, Baixuan**	Identification and Validation of 3D Viscoelastic Parameters of Polymer Using Digital Image Correlation **Yue, Lingyu**
11:40 a.m.		Fracture Mechanisms of Human Femoral Cortical Bone as a Function of Loading Rate **Weerasooriya, Tusit**	Investigation of Shear and Fracture Properties of Fiber reinforced Composite Laminates using DIC **Merzkirch, Matthias**
12:00 p.m.	**Lunch**—Pacific Northwest Ballroom		
Thursday Afternoon October 17, 2019	**HIGH SPEED 2** *Chair(s):* **Alessandro Vieira**	**BIO 2** *Chair(s):* **Jean-Noël Périé**	**MATERIAL 5** *Chair(s):* **Benoit Blaysat**
1:00 p.m.	Toward Quantitative High Resolution Ultra-High Speed Imaging **Vinel, Adrien**	Combination of Point- And Surface-Based DIC Measurements with Computed Tomography Data **Acun, Burak**	Global Stereo-DIC based on Finite Elements for the Identification of the Parameters of a Constitutive Law **Colantonio, Guillaume**
1:20 p.m.	Image-Based Stress Reconstruction: A Step Toward a Contactless Dynamic Probing Test **Seghir, Rian**	Hybrid Experimental-Modeling-Computational (HEMC) Methods: Validation of Microstructurally Inspired Deformation and Failure Models of Human Skull **Weerasooriya, Tusit**	Stereo Digital Image Correlation on Vibrating Materials for Damage Detection **Lorenzo, Nicholas**
1:40 p.m.	Simultaneous Comparison of High Speed Digital Image Correlation and Polarization Imaging **Shannon, Ryan**		Non-Parametric Correction to History Dependent Material Constitutive Laws from Displacement Field Measurements **Réthoré, Julien**

Detailed Schedule

	BROADWAY	WEIDLER	HALSEY
Thursday Late Afternoon October 17, 2019	VOLUMETRIC *Chair(s):* **Brian Bay**		PETROLEUM *Chair(s):* **Mehdi Mokhtarim**
2:20 p.m.	**Coffee Break**—Multnomah/Holladay Foyer		
3:00 p.m.	A Fast GPU-Based FFT Interpolant Algorithm for Synthetic Image and Volume Deformation **Fayad, Samuel**		Evaluation of Tensile Properties of Transversely Isotropic Rocks Using Brazilian Disc Test and Digital Image Correlation **Naik Parrikar, Prathmesh**
3:20 p.m.	Fast Adaptive Augmented Lagrangian Digital Volume Correlation **Yang, Jin**		Estimation of Geo-material Deformation and Strain using Finite Element Based DIC and Smooth Particle Hydrodynamics (SPH) **Reddy, Chamanth**
3:40 p.m.	Internal Full Field Strain Measurement of Composites Material using X-ray Digital Radiography and Digital Image Correlation Techniques **Palliyaguru, Upul**		Evaluation of Fracture Toughness of Laminated Rocks using Digital Image Correlation **Naik Parrikar, Prathmesh**
4:00 p.m.	A Rotating Specimen Load Frame for CT Scanner and DVC **Arzoumanidis, Alex**		

Acceptance and Verification of DIC Systems with Reference to VDI/VDE Guidelines

Oliver Witzel, Burak Acun, Markus Klein, Thorsten Weikert

To increase acceptance and trust in DIC systems, it is important to provide users with more information about the performance capability and status of their systems. Therefore, a standard test procedure is needed. To define such a test procedure the VDI (The Association of German Engineers) developed a guideline for an acceptance and verification test for DIC systems (VDI-2626). The implementation of such a test with the addition of further measurement methods for instance a reference point-based procedure is quite challenging as they can become quite time and cost consuming. Therefore, a test based on the VDI-2626 guideline was developed and extended with the procedures from another guideline for optical 3D measuring systems (VDI-2634-1). The result is a testing procedure with high repeatability and low-cost artifacts that cover a large range of measuring applications (e.g. point-based, pattern-based, 3D coordinates, strain). The procedure uses reference scale bars which have been calibrated with traceable certification (DAkkS). By positioning the scale bar at different positions in the field of view and checking for the length deviation, the quality of the calibration, the calibration object and the measuring system can be determined. In addition, a test according to the VDI-2626 guideline is performed for the determination of the zero-deformation deviation. By moving a rigid plate with speckle pattern within the calibrated measuring volume of the DIC system and analyzing the remaining strain and displacement distribution (after rigid-body movement correction) two quality parameters (Zero Strain Deviation and Zero Displacement Deviation) can be derived as a measure for the quality of the system.

VDI 2626: Directive and Hybrid Calibration Method, Implemented and used in VIC

Hendrik Pulju– isi-sys GmbH; Peter Mäckel–isi-sys GmbH; Bachir Belkassem–Royal Military Academy Belgium; Hubert Schreier–Correlated Solutions Inc.

The new VDI 2626 directive for the verification and acceptance of a Digital Image Correlation (DIC) setup, which was already presented for the first time at iDICs 2017, is mainly based on a so-called "zero test" of strain and displacement as well as on traceable shifts of a rigid body. At first, a zero test or rigid body shift seems inadequate for the verification of a strain measurement. However, the zero test already includes a perspective deformation of the speckle pattern in the image plane, when recorded at different viewing angles and locations within the measurement volume. Additionally, local distortions and imperfections of the optics are superposed. Hence, the zero test is an essential part to verify a DIC strain measurement but does not address the need to validate strain measurement accuracy beyond rigid body motions.

Development of Laboratory Experiments Utilizing StereoDIC for Accurate Measurement of In-Plane and Out-of-Plane Deformations

Michael A. Sutton–University of South Carolina; Ali Fahem–University of South Carolina; Ian Adkins–Correlated Solutions, Inc.; Micah Simonsen–Correlated Solutions, Inc.; Nicholas Lovaas–Correlated Solutions, Inc.; Hubert Schreier–Correlated Solutions, Inc.; Stephen McNeill–Correlated Solutions, Inc., Sreehari Rajan–University of South Carolina

Utilizing the recently developed, low cost educational StereoDIC measurement system, VIC-EDU, for non-contacting deformation measurements during mechanical loading, the development of several solid mechanics laboratory experiments targeted for undergraduate engineering students is described.

Design and Application of a Reference Standard for the Calibration of Full-field Optical Strain Measurements in Full-scale Test Applications

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Even with the widespread adoption of digital image correlation techniques, it is still not always a common practice to calibrate the optical system as part of the testing process. Without performing a calibration on the optical system, it is impossible to determine the uncertainties associated with its measurements. This research details the development of a calibration reference standard based on a design from the Validation of Numerical Engineering Simulations: Supporting Action (VANESSA) Project. The design and loading for the reference standard were based on that of a cantilever beam in simple bending. Two potential loading modes could be enabled, one loading the beam in a low moment of inertia (Low I) configuration and one loading the beam in high moment of inertia (High I) configuration. To produce the reference standard more economically and more accurately than milling it out of a solid metal billet, an innovative manufacturing method was employed that increased accuracy, reduced costs and allowed the reference standard to be scaled up in size for use in load frames or for use in full-scale structural testing applications. An in-depth description of the analytical equations guiding the calibration process is provided along with details of the MATLAB based software used to perform the calibration. This research study also describes the process for recreating a camera setup for performing a camera calibration on the optical setup used for a full-scale structural test. A final case study involving optical strain measurements on a full-scale aircraft component is provided. This study was conducted for two sample cases, using a small reference standard in the Low-I configuration, as well as a larger reference standard in the Low-I configuration. The result showed that the camera system was in calibration for all sample cases. The maximum uncertainties were +/- 117 microstrain for strain ranges of 2000 microstrain and above for the case of small reference standard in the Low-I configuration, and +/- 102 microstrain for strain ranges of 2000 microstrain and above for the case of large reference standard in the Low-I configuration.

Utilizing Three-Dimensional Digital Image Correlation (3-D DIC) on Space Flight Hardware

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NASA's next exploration mission to Mars, Mars 2020, is scheduled to launch in July of 2020. This mission uses a similar architecture to the previous science mission to Mars, the Mars Science Laboratory, or MSL. In fact, the initial plan was that Mars 2020 would use the spare MSL heat shield (HS) structure, termed HS#1, however it failed during acceptance testing in April 2018. The redesigned Mars 2020 HS (HS#3) adopted a simpler load application process (entry pressure was applied through vacuum - HS#2) compared to the method used in HS#1 (external pressure via a pressurized airbag). To guard against failure, full-field photogrammetry real-time coverage of the entire OML surface of the HS was proposed by the NASA Engineering and Safety Center (NESC) team who participated in the HS#1 failure investigation. The HS#3 proof test was conducted with three low-speed, high resolution 3-D DIC systems, as shown in Figure 1. The test article was the actual flight hardware that would have the thermal protection system bonded to the surface post-test and flown to Mars. This required that HS#3 be returned in pristine condition and a very limited list of materials allowed to contact the surface. Thus, typical methods of applying a contrasting speckle pattern could not be used. A removable vinyl vehicle wrap with a printed on speckle pattern was evaluated and approved for use in this test. The 3-D DIC systems were spaced 120-degrees apart around the circumference of the test article to provide complete monitoring of strains and displacements on the HS#3 surface. The Real-Time module of VIC-3D was used to provide near instantaneous comparison of the measured-predicted behavior and to monitor the limits imposed to prevent the HS from failing during loading. Post-processing of the data was done using the built-in functions of the VIC-3D software to fully capture, visualize and understand the response. More specifically, the individual camera systems were "stitched" together, to generate a complete data overlay of the entire HS. Once the systems were merged into a global data set, the data set was rotated to align with the FEM coordinate system. The nodal mesh locations were then imported into the VIC-3D global data set, and extracted using the software. DIC results were compared to data from other instrumentation, such as strain gages and linear variable displacement transducers, as well as compared to computational modeling predictions to assess the validity of the models.

Dynamic Deformation of Cover Glass in Mock Phone for Different Orientations of Drop

Charandeep Singh, Ryan Vetter and Sergey Shubin–Corning. Inc

With more than 1 billion smart phones sold in 2018, handheld devices remain one of the most lucrative industry. Each year, multiple Original Equipment Manufacturer (OEM) introduce new and improved devices with superior performance than the previous years model. Along with user interface and handheld device's mechanical reliability is also improved. Yet, instances remain where the cover glass may break. Number one reason for cover glass failure in handheld devices is failure upon drop on rough surface such as asphalt. During drop event, handheld device experiences bending and sharp contact at same time. Bending of the handheld devices is a function of height of drop and angle or orientation of the drop. Amount of the bending experience by phone in different orientations of drop is still unknown. Objective of this study is to quantify the bending in cover glass in mock phone and commercially available phones when dropped from various height and angles. High speed Digital Image Correlation (DIC) technique is use to measure in-situ localized and global bending of the cover glass. Mock phone is dropped on top of thick clear glass surface which acts like a drop surface. Two high speed cameras are placed directly under the glass to measure dynamic deformation on cover glass during and after the drop event. Images are then imported in DIC system and full field out of plane dynamic deformation field is obtained. FEA model is also prepared to predict stresses experienced by the cover glass during dynamic event. Trajectory of phone before and after the drop is captured by two high speed cameras. This data along with full field dynamic deformation field from DIC is used to validate the FEA drop result. This study helps in measuring the critical angles of drop, establish relationship between local and global bending of the phone with height and orientation of drop.

Leveraging Emerging Technology at the Speed of Change in Human Space Flight

Ryan Shannon–United Launch Alliance

Testing at the speed of change requires innovation because test schedules change, scope creeps, and new technologies emerge. This contribution demonstrates how emerging Digital Image Correlation (DIC) technology can be implemented in parallel with heritage aerospace separation testing approaches to achieve a higher standard in separation model test correlation data products to support safety in human spaceflight. 2D and 3D DIC Aeroskirt separation motion measurements are compared for full-scale testing within a high altitude testing chamber. A novel Virtual Digital Image Correlation (ViDIC) process is described and demonstrated to be valuable in determining optimal DIC parameter settings prior to testing. Leveraging DIC in support of Aeroskirt jettison testing provides superior model correlation products, better addresses test data anomalies, and has the potential to answer unforeseen future concerns without retesting to enable testing at the speed of change.

An Overview of DIC Technology Applications at Boeing

Alessandro Vieira–Boeing (iDICs board member); Dr. James Grossnickle–Boeing

Digital Image Correlation (DIC) has been used at Boeing for the past 14 years in a wide range of applications. This article will provide an overview of most recent applications in the areas of structural testing, environmental, propulsion and manufacturing. For each application, we will present the measurement challenge, the benefits of deploying a full-field measurement solution and how DIC was able to provide unforeseen results. In addition, we will discuss the findings when comparing DIC to traditional methods and our continue efforts to quantify measurement uncertainties and data accreditation. Finally, we will present a technology road map and discuss how we envision this technology being deployed in the near future.

Full-Field Correlated Mechanics of Cross-Laminated Timber

Dietrich Buck, Olle hagman–Luleå University of Technology, Sweden

This work evaluated the effect of timber quality features on the full-field mechanics of cross-laminated timber (CLT) panels. Panels were individually subjected to destructive out-of-plane loading in the principal panel orientation. A digital image correlation (DIC)-based technique was applied for non-contact full-field measurement and analysis of panel mechanics. The results for 50 layers show that the stiffness of conventional CLT is largely reduced by the shear resistance of transverse layers. Notably, heterogeneous timber features, such as knots, can reduce the propagation of shear. These results suggest an optimized panel assembly strategy that can be generalized: If shear is dimensioning in an area, e.g. the transverse or the central longitudinal layer, the use of knotty timber in that layers can reduce shear propagation. Knots in the compression zone in longitudinal layers have some negative impact, but knots have the largest negative impact in areas of longitudinal layers under tension. Therefore, it is suggested the current grading criteria in the CLT standard be revised to allow the use of more knotty timber in the transverse layers of CLT; doing so could allow a more profitable use of otherwise low-grade timber while producing a stiffer product. The potential of panels constructed according to such an approach may allow new applications for CLT in timber construction and should be further explored.

Mixed Finite Element-DIC Technique to Detect Unseen Abnormalities of a Structure Using an Inverse Approach

Mehrdad S. Dizaji; Devin K. Harris

Image-based techniques are being extensively deployed to measure full field surface measurements such as displacements or strains under loading. 3D Digital Image Correlation (3D-DIC) is one such technique that is frequently used in experimental mechanics to quantify full-field strain measurements. This paper studies the feasibility of detecting interior defects inferred from discrepancies in the constitutive properties such as elasticity modulus distribution of a three-dimensional heterogeneous/homogeneous sample using limited full-field surface measurements within an inverse problem framework. No assumptions about local homogeneities or the modulus of elasticity distribution were made a priori. The proposed technique is called 3D Digital Image Correlation Tomography for Structural Identification. The concept centers around recovering unseen volumetric defect distributions within the interior of three-dimensional heterogeneous space of the structural component using 3D-DIC for structural identification (St-Id). The approach leverages full-field surface deformation measurements of structural elements as ground truth measurements coupled with a finite element model updating process using a novel hybridized parallel optimization algorithm. This work explores this proposed concept through a case study on a structural test specimen analyzed using 3D-DIC for St-Id. As a proof of concept, the results of this paper illustrate the potential to localize internal defects from surface observations and demonstrates the potential for new opportunities to characterize internal properties of materials from their mechanical property distribution and condition state.

Evaluation of the Cement Bond Integrity by Using Digital Image Correlation (DIC) Technique

Yuxing Wu–University of Oklahoma; Saeed Salehi–University of Oklahoma; Mehdi Mokhtari–University of Louisiana

Cement sheath is an important barrier to provide a hydraulic seal and establish zonal isolation, preventing fluid communication in the wellbore. A loss of zonal isolation costs a complicated remedial operations and induces negative environment impacts. The goal of this study is to investigate cement bond integrity in casing-cement-formation system by using digital image correlation (DIC) technique. To achieve the objective, diametrically compressive experiment is developed for a casing-cement-formation system. DIC is employed to examine strain distribution along the casing-cement and cement-formation interfaces. The compressive test system is utilized to record the relationship between applied load and axial strain. The effects of casing eccentricity, mud contamination, and lithology of cement on bond strength are investigated. For the convenience of comparison, concentric casing-neat Class H cement-sandstone are used as a reference sample. The experimental results show that for both the eccentric and mud contamination cases, the bond strength is weaker than the reference case and failure initiates at the casing-cement interface. The comparison of sandstone and shale shows that for sandstone, bond fails at the casing-cement interface while failure occurs at the cement-formation interface in shale due to the development of mechanical interlocking bond at the sandstone-cement interface. This study provides a novel method to test the interfacial bond failure in the casing-cement-formation system under diametric load. The DIC provides the strain maps to illustrate displacement at the interfaces visibly and helps to analysis the debonding around the samples.

Performance Evaluation of Three-Tab Shingles with ual Sealant Strips Subjected to Wind Gusts Up to 150 Mph Using Stereo Digital Image Correlation

Troy Myers, Sreehari Rajan and Michael A. Sutton–University of South Carolina

Simulations employing a two-dimensional beam-on-elastic-foundation model have shown that dual sealant strips placed at optimal positions on a three-tab asphalt shingle reduces the applied energy release rate, G, by a factor of fourteen. To experimentally quantify the performance of an asphalt shingle with dual sealant strips, a shingled plywood facsimile roof structure is constructed, mounted to a rigid steel structure at a 10o angle relative to wind direction and then subjected to 241km/hr (150mph) winds that are commonly observed in Category 5 hurricanes measured. To measure the response of a shingle adhered to the roofing facsimile using dual sealant strips, a StereoDIC system consisting of two 12MP CMOS cameras with 12mm lenses and a pan angle of 8o is mounted to a nominally rigid frame structure and oriented to view the 0.5m x 0.5m shingle region of interest. Since preliminary studies demonstrated that any paint layer will significantly alter the deformation of a shingle, shingles were selected with light-colored UV-absorbent mineral granules to provide the intensity contrast and speckle sizes required for accurate StereoDIC displacement measurements. In this study, the time history of measured shingle deformations, with emphasis on uplift displacement field, is measured over a 90 minute time span for wind speeds up to 241km/hr (150 mph). Results from this study for both single sealant and dual sealant adhesive layers will be reported and compared to quantify the incremental improvements in shingle response that are observed.

On the Pattern Induced Bias in DIC

F. Sur–Université de Lorraine; B. Blaysat–Université Clermont Auvergne;
M. Grédiac–Université Clermont Auvergne

Digital image correlation (DIC) gives measurement of displacement fields on the surface of specimens subjected to mechanical tests. It basically consists in matching subsets extracted from reference and deformed images by minimizing an optical residual. It turns out that the marking of the tested specimen, usually a speckle pattern, plays a role in the accuracy of the method. Taking our inspiration from the literature on stereoscopy, we show that a phenomenon similar to the so-called fattening effect can be observed in the displacement fields. In particular, it can be demonstrated that the estimated displacement is an average over the subset of the true and unknown displacement weighted by the gradient of the underlying image. The gradient distribution is consequently a source of measurement bias, together with the interpolation scheme required by DIC. We give a closed-form expression of measurement bias caused by marking and interpolation scheme. Numerical assessments illustrate and support the proposed mathematical analysis. In short, the contribution of this paper is a complete characterization of the measurement bias in DIC, and a holistic view of various phenomena which were previously discussed separately by several authors.

Minimizing Pattern Induced Bias in Digital Image Correlation

Samuel Fayad-Sandia National Laboratories; Phillip Reu-Sandia National Laboratories;
Tom Seidl-Sandia National Laboratories

Digital image correlation (DIC) is an optical metrology method widely used in experimental mechanics for full-field shape, displacement and strain measurements. The required strain resolution for engineering applications of interest mandates DIC to have a high image displacement matching accuracy, on the order of 1/100th of a pixel, which necessitates an understanding of DIC errors. In this paper, we examine a spatial bias term that has been almost completely overlooked. It causes a persistent offset in the matching of image intensities and thus corrupt DIC results. We describe this pattern-induced bias (PIB) [1] and show that the PIB error occurs in the presence of an undermatched shape function and is primarily dictated by the underlying intensity pattern for a fixed displacement field and DIC settings. In this paper we demonstrate this error and quantify its magnitude both experimentally and with synthetic images. Additionally, protocols to minimize this error are implemented in the DIC algorithm, as well as in experimentation.

New Method for DIC Uncertainty Quantification in Industrial Environments

T. Siebert–Dantec Dynamics GmbH; K. Dvurecenska–University of Liverpool; E. Hack– Empa; G. Lampeas– Industrial Systems Institute; E. Patterson–University of Liverpool; K. Splithoff–Dantec Dynamics GmbH; E. Szigeti–Airbus Operations Ltd.

The qualification of the measurement uncertainty is essential for any measurement technique, but for Digital Image Correlation (DIC) it is still not fully resolved and implemented. There are different approaches used to qualify or quantify the uncertainty, associated with the measurement. These include noise floor determination, measurement of rigid body movement, error propagation method, use of physical reference materials and others. Different approaches have their advantages and limitations, but none is able to provide full-field 3D uncertainties covering the complete measurement chain. Within the MOTIVATE Clean Sky 2 project, one aim was the development of a specific method for quantification of DIC measurement uncertainty in experiments performed in industrial environments . The new method is based on the use of the calibration target, employed for the calibration of the DIC system, combined with a rigid body translation between the object and the DIC system. The target is used to determine the rigid body translation which is then applied to the DIC data before translation and compared with the data after the translation. The method is easy to integrate in the measurement work flow, does not need additional expensive equipment and allows the determination of the displacement uncertainties taking all environmental conditions into account. A detailed description of the method and results are given. The new method is applied on a compression test of a fuselage panel and the results are verified using a uni-axial translation stage.

Experimental Configuration Calculator for 3-D Image Correlation

Stephen R. McNeill–Correlated Solutions, Inc

The experiment setup for Stereo DIC is determined by many factors, including selection of cameras and lenses, placement of cameras and required lighting to obtain the required field of view (FOV). Once these are selected, additional considerations include aperture setting for lenses, required displacement sensitivity and the optimal speckle size for the required FOV. One of the factors that help determine these requirements is the expected measurement volume based on estimates for the expected amount of motion that the object will incur during an experiment (e.g., both out-of-plane and in-plane motions) for the FOV (e.g., size of region where measurements are needed). The spatial position and separation of cameras in a stereo configuration may be constrained due to limitations on available space, placing limits on the sensitivity of the system for out-of-plane displacements Given camera lenses, camera placement, and camera sensor information, there are available calculators to determine the resulting FOV. Given lens parameters, lens aperture and circle of confusion (which can be related back to pixel size), there are separate calculators to determine the depth of field (DOF).There are also available calculators to determine measurement sensitivity given the stereo camera configuration parameters. Thus, if the required information is available, then FOV, DOF, system measurement sensitivity and the available measurement volume can be determined. This presentation will detail the development of a calculator which allows the user to enter specimen information (e.g., size), expected motion, available camera placement and orientation data, desired sensitivity, available cameras and lenses, system constraints) and then generate the required experimental configuration so that the system will have the required field of view and measurement volume for the application of interest, eliminating the need for time-consuming, iterative processes oftentimes required to determine system configuration for each application.

Application of a Three-Dimensional Digital Image Correlation for Measurement of Clad Tube Deformation under Transient Heating and Pressurization

Dong-Hyun Kima– Korea Atomic Energy Research Institute, Hanyang University; Gyeong-Ha Choi–Korea Atomic Energy Research Institute; Hyochan Kim–Korea Atomic Energy Research Institute; Chan Lee–Korea Atomic Energy Research Institute; Sung uk Lee–Korea Atomic Energy Research Institute; Hak-Sung Kim–Hanyang University

In this work, multi-D deformation of clad tube under transient heating and pressurization conditions during burst experiment was measured by a three-dimensional (3D) digital image correlation (DIC) system. A two-camera stereovision technique was employed to measure multi-D full-field deformation of the clad tube. Additionally, both bandpass filter and heat resistant coating were used to apply the 3D DIC system under high temperature condition. Before the burst experiment, accuracy of the 3D DIC system was first validated by a series of proposed methodology. Based on the validation, the burst experiment was performed using an experimental setup named 'Facility to Investigate Single-Rod Behavior In Transient' (FISRBIT). During the experiment, the clad tube was internally heated and pressurized in an inert gas atmosphere until burst of the clad tube occurs. Deformation of the clad tube was measured by both the 3D DIC system and linear variable differential transformers (LVDTs) while temperature of the clad tube was measured by thermocouples (TCs) attached to surface of the clad tube. As an experimental result, the established 3D DIC system could successfully measure in-situ and real-time large deformation as well as full-field multi-D strain results such as hoop, radial, and axial strains of the clad tube under a high-temperature condition of more than 700°C. Additionally, the 3D DIC system more effectively measures surface deformation of the clad tube than the LVDTs as an advantage of the non-contact measurement technique.

3D Micro Stereo Sensor for Digital Image Correlation

Hendrik Pulju –isi-sys GmbH; Peter Mäckel–isi-sys GmbH

The micro stereo sensor system which was established in 2018 has been evolved for full field residual strain measurement by digital image correlation (DIC) according to the hole drilling method for various materials. The full field and non-contact measurement is especially advantageous to explore residual stresses within composite structures compared to the conventional method based on point measurements by strain gauges. The development here is based on the 3D micro stereo sensor of isi-sys GmbH in its second version. The sensor is designed to be used in combination with the VIC 3D software of Correlated Solutions Inc., USA. The modified sensor design for residual strain measurement enables a drilling process without removing the sensor. The stereo sensor set up is designed for a field of view of about 8mm x 7mm @ 5Mpx and now even for 4mm x 3.5mm @ 5Mpx with 2:1 magnification lens which leads to a resolution of 1,77 µm. Despite the high spacial resolution and strain sensitivity the signal to noise ratio is good even for very small residual strains. This sensor will be tested for compliance to the VDI guideline 2626.

Comprehensive Layer Monitoring During Selective Laser Melting with Stereo-DIC Powder Surface Profiling

Daniel P. Mosher–Oregon State University; Brian K. Bay–Oregon State University

Selective Laser Melting (SLM) and related techniques show paradigm-shifting potential for the metal additive manufacturing industry, yet problems with consistency, process control, defect detection and component qualification remain. Various visible light and thermal image monitoring methods have been investigated for SLM process improvement, but spatially resolved, quantitative characterization of the full powder surface is lacking in single camera methods, with most systems simply assume a flat powder surface of consistent thickness. Noting a similarity between the appearance of metal powders and digital image correlation speckle, we investigated the use of stereo-DIC as a means of powder surface profiling. Although metal powders are under-resolved with respect to optimal speckle for typical powder bed sizes (8"x6", 200mm x150mm), we were nonetheless successful in surface profiling at good precision (~10 microns) for both unfused and fused surfaces under controlled lighting conditions. We then integrated stereo-DIC monitoring into a commercial SLM system and unobtrusively collected images for all fresh and fused layers of typical builds, developing comprehensive volumetric maps of the build process in the form of quantitative surface height profiles. We documented a variety of phenomena: large variations in powder surface height, interaction between powder spread and underlying part geometry, varying depth of powder in different fusion regions, wear of the spreader bar blade during individual builds, slag particle dragging and subsequent part focal defect formation. We envision a broad range of uses for this relatively simple technology in both the development and use SLM and other powder additive technologies, particularly if systems are designed to facilitate stereo-DIC monitoring, as the combination of measurement precision and area of coverage is unrivaled. This presentation will describe the measurement system and data processing methods using actual component builds as examples.

Fluid Mechanics Application of DIC: Liquid Sloshing

Chi-Hui Chien–National Sun Yat-Sen University; Ting-Hsuan Su–National Sun Yat-Sen University; Chao-Jian Huang–National Sun Yat-Sen University; Yuh-Jin Chao–University of South Carolina; Wei-Li Yeh–National Sun Yat-Sen University; Poh-Sang Lam–Savannah River National Laboratory

Digital image correlation (DIC) method has been used traditionally and extensively in solids or structures. In this talk, we extend DIC to a particular fluid mechanics area, namely, sloshing of liquid inside a container. Liquid sloshing is one of the major issues for the storage subjecting to ground movement or earthquake and dynamic movement of liquid in fuel tanks during transportation. Numerical simulations have been performed by finite difference or finite element methods. However, simulations are based on many assumptions and the results sometimes cannot fully describe the actual movements of the liquid inside the tank. On the other hand, sloshing experiments are usually conducted with two-dimensional images taken from the side of a liquid tank with a high speed camera. This renders only limited information because liquid sloshing is three-dimensional in nature in majority of the tank structures. This paper is aimed to develop an experimental method, which is empowered by the state-of-the-art digital image correlation (DIC) technique that is capable of measuring three-dimensional (3D) surface profile of a sloshing liquid. The 3D sloshing surface profile of the liquid in a container oscillating horizontally was investigated to demonstrate the technique. The effects of different liquid depth on the surface profile of sloshing liquid were then studied.

DIC Analysis to Investigate the Post-Overload Fatigue Crack Growth Behavior

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The present article analyzes the crack growth behavior after the application of a 100% overload cycle. The full-field displacement data obtained using 3D-DIC provides important information about local and global behaviors of cracked specimens. Important fracture parameters can be obtained from the region surrounding the crack tip, such as Stress Intensity Factor (SIF), Crack Opening Displacement (COD), J-integral, crack closure, crack blunting and plastic zone size. From the experimental results, it was observed the presence of nonlinear behavior during the post-overload transient crack growth even after the crack has propagated out of the region hypertrophied by the overload. All experimental observations from DIC analysis are shown and discussed in detail.

A Model-Free Analysis of Small Scale Yielding to Generalized Plasticity Transition During Mixed-Mode Fatigue Crack Propagation

Raphaël Langlois–Ecole Centrale de Nantes; Julien Réthoré–Ecole Centrale de Nantes;
Michel Coret–Ecole Centrale de Nantes

Great amounts of data have been made readily available thanks to the development of full-field measurement techniques for kinematic or thermal fields. These data are classically used in Finite Element Model Updating schemes (or equivalent) in order to find the material parameters of a prescribed behavior law. The optimal parameters of the prescribed stress-strain relation are mainly obtained on regular homogeneous tests. The identified law is then extrapolated to material states not explored by the performed tests. The recent introduction of "Data-Driven" simulations and identification methods allows to circumvent the modeling bias inherent to the classical approach. "Data-Driven Identification" takes as inputs the displacement measured by DIC and the load cell data. The outputs are the material states which sample the stress-strain manifold and the mechanical states which are the compatible stresses and strains of the test. The former can be used for 'Data-Driven Simulations'. The use of the latter is the topic of this paper. In this paper, we investigate the propagation of fatigue cracks in modified steel SENT specimens. The presence of a crack activates new mechanical states, which enrich the test. But the drawback is that a crack is an evolving boundary condition that needs to be taken into account. Results for cyclical plasticity will be presented and compared to a linear isotropic hardening law. The main result is that the identified behavior presents both isotropic and kinematic hardening.

Determining Fracture Toughness of Composite Joints: A New Matlab Software and Methods Comparison

Peter Caltagirone–Colorado School of Mines; Aaron Stebner–Colorado School of Mines

Understanding adhesive behavior is an increasingly important aspect to predict how a system of composites will behave. Many adhesive standards exist to determine properties such as shear strength, tensile strength, and fracture toughness. ASTM D5528 is one such standard, which defines how to calculate the fracture toughness of an adhesive using a peel test. The standard specifies that markings be placed on the sample to measure the crack length and calculate the fracture toughness. While this allows one to determine the fracture toughness, the process is extremely time consuming, tedious, and prone to human error when marking the sample. A Matlab toolbox was written to automatically analyze crack propagation from digital images, create compliance plots, and export the fracture toughness calculated three different ways to an MS Excel file. Rather than using 18 points of data as defined in the traditional method, the program computes the fracture toughness using hundreds of points, reducing noise and error. Xu et al. defined another method to calculate the fracture toughness using only the force and displacement during the test [1]. The reliability of these three methods for calculating the fracture toughness of an adhesive is assessed and the computational method is found to be most reliable based on the calculated fracture toughness and repeatability of results. [1] W. Xu, Z. Z. Guo, Y. Yu. A Double Compliances Method for Measuring the Mode I Interlaminar Fracture Toughness of Composite: Theory and Applications. Proceedings of the 18th U.S.-Japan Conference on Composite Materials (2018). DOI: 10.12783/asc33/25936

Effect of Adhesive Thickness and Strain Rate on Mode I Fracture Toughness of Polymer Modified Bitumen - An Experimental Investigation Using Stereo DIC

Sreehari Rajan–University of South Carolina; Troy Myers–University of South Carolina; Michael A. Sutton–University of South Carolina

The traction-separation relationship and the corresponding critical energy release, GIC, for a polymer-modified bitumen are measured using a double cantilever beam experiment combined with stereo digital image correlation (StereoDIC). In addition, the opening displacement and root rotation at the crack tip are measured using StereoDIC measurements synchronized with the applied load. These measurements are used to determine the average strain rate at the crack tip in the adhesive layer, providing a metric for rate effects leading up to the onset of separation. For low crack tip strain rate, ductile fracture is observed that is characterized by slow crack growth and a large crack tip process. For higher strain rate, brittle fracture is observed that is characterized by sudden, rapid crack growth and a significantly smaller crack tip process zone. Results shown that GIC is a linearly increasing function of adhesive thickness for strain rates corresponding to the ductile fracture region. These findings are consistent with the observation that the fracture process zone (and hence the volume of material involved in the fracture process) also increases with adhesive thickness. Conversely, results also show that GIC is independent of adhesive thickness for higher strain rates where brittle fracture occurs. This result is consistent with the observation that the crack tip process zone is essentially the same size and fully contained in the adhesive layer for all strain rates used in our experiments when the bitumen layer thickness is reduced below a limiting value. Review of the existing literature shows that the trends observed in this study are consistent with previous experimental studies on similar material systems.

Application of Stereo 3D Digital Image Correlation in Mach 2, 4, and 6 Wind-tunnels

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Structures operating in environments with faster than the speed of sound flow will experience extreme acoustic and thermal loading conditions including complicated aero-thermal-mechanical coupling. Performing research in such environments requires advanced testing facilities and instrumentation. This work focuses on the application of stereo 3D digital image correlation (3D DIC) in three wind tunnels at flow conditions of Mach 2, 4, and 6. Both rigid and flexible structures are examined to quantify error due to flow distortion and demonstrate the ability of 3D DIC in such environments.

ODS Detection in Modern DIC Software Environment

Thorsten Weikert; Burak Acun; Oliver Witzel; Markus Klein

The detection of operational deflection shapes is a standard test for many parts and components in modern industry. The goal of these vibration tests is to reach long lifetimes, high security margins and customer content. To achieve information about the behaviour of distinct parts under operational circumstances test and more and more often simulations are used. To validate these simulations, or even increase their quality by evaluating input parameters, the corresponding parts need to be measured too. To not disturb the test and the behaviour of the part under load the measurement system should have the least amount of interference on the test itself as possible. As a non-contact measurement method, digital image correlation provides solutions for such measurement tasks. Traditional measurement methods like accelerometers, wire-sensors and laser-vibrometers are used to measure accelerations and movements. But the installation of these measurement techniques is complex and time-consuming. With this come the demands of engineers and technicians of automotive, aerospace consumer goods and civil engineering industries for easier and faster measurement methods and techniques for the numerical simulation comparison. The DIC technique combined with a powerful software combines many advantages: non-contact measurement, the detection of up to thousands of measurement points in space and time and software solutions for evaluation and comparison. Even the detection of operational deflection shapes is possible as well as the comparison against simulated data.

Vibration Modes Measurement of a Thin Plate using Single High Speed Camera with FE Model

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Huan Shen–Nanjing University of Aeronautics and Astronautics;
Lin Yue–Nanjing University of Aeronautics and Astronautics;
Wendong Zhang–Aircraft Strength Research Institute Aviation Industry Corporation of China

Digital image correlation (DIC) has been developed for decades as a non-contact optical technique of full-field displacement and strain measurement using precise and costly digital cameras with high image resolution and used in many applications, including material characterization, temperature deformation, fracture analysis, vibration analysis and so on. Traditional sensors, like contact or single-point types, are difficult to obtain the accurate and full-field vibration information in thin-wall parts measurement with experimental mechanics method. Simultaneously with the development of high-speed camera technology, vibration modes measurement based DIC is more and more attention, such as a series of beams vibration modes measurement research recently that is fit for the view of high frame rate and decreased resolution. In this paper, a single high-speed camera is used to DIC images acquisition that which keeps an inclination angle between direction of optical axis and normal direction of thin plate. So that the vibration displacement response in nomral direction could be derived by the displacement filed results from single camera images through DIC algrithom. Then, it can be used to vibration mode parameters identification directly based EMA, such as p-LSCF method. Meanwhile, in order to meet the challenge of small strain measurement, less than 300 microstrain, the strain modal and vibration response is calculated combining with the FE-model. Results show that the nature frequency and mode shape are idencificated well comparing with FE-model and strain response can be derived also.

Vibration Based Stitching Technique to Obtain Deflection Shapes using DIC

Javad Baqersad–Kettering University; Vanshaj Srivastava–Kettering University;
Yaomin Dong–Kettering University

The automotive and aerospace industries are increasingly using light-weight material to improve vehicle performance while reducing fuel consumption. However, using light-weight material can increase the air-borne and structure-borne noise. Thus, special attention needs to be paid in designing the vehicle body structure and evaluating its dynamics. In order to accomplish this, modal analysis is conventionally used. In this technique, the structure is excited using an impulse hammer or a mechanical shaker, and the response is measured using accelerometers. However, using contact-based transducers can mass-load the structure and can only provide data at a few discrete points. In the last decade, stereo-photogrammetry and three-dimensional digital-image correlation have received special attention in collecting operating data for structural analysis. These non-contact optical techniques provide a wealth of distributed data over the entire structure. However, the stereo-camera system is limited by the field of views of the cameras and can only measure the response on the parts of a structure for which cameras have lines of sight. Therefore, a single pair of DIC cameras may not be able to provide deformation data for an entire structure. A multi-view 3D DIC approach, however, can be used to predict the vibrational characteristics of a full vehicle. A pair of DIC cameras is passed over the entire vehicle to capture the deformation data of each field of view. The measured data includes the geometry and displacement data, which is mapped into a global coordinate system using 3D transformation matrices. The obtained data in the time domain for each field of view is transformed to the frequency domain using a Fast Fourier Transformation (FFT) to extract the operational deflection shapes and resonant frequencies for each field of view. The obtained deflection shapes are scaled and stitched in the frequency domain to extract the operating deflection shapes of the entire vehicle.

DICe: An Open Source DIC Platform for DIC-related Research

Dan Turner–Sandia National Laboratories; Tom Seidl–Sandia National Laboratories; Phil Reu–Sandia National Laboratories

This talk will present an overview of the Digital Correlation Engine (DICe) software and provide an entry point for DIC researchers looking for an open source platform in which to try new algorithms. DICe has capabilities in object tracking, 2D and stereo DIC, both local and global methods, post processing DIC data, and processing high-speed video. DICe also includes an interface to OpenCV, which provides a number of opportunities for advanced algorithms that employ computer vision techniques combined with machine learning. DICe builds on Windows, Mac, and Linux, making it highly portable. High-level information about active areas in development in DICe will be presented as well as basic information about how to download and get started developing new routines and improvements. The intended audience for this talk is university professors or graduate student pursuing DIC-related research who are looking for an efficient way to explore algorithmic development. The intended audience also includes commercial DIC code developers looking for a lightweight platform to experiment with new ideas or to stay informed on advanced methods being developed in the research community. Ultimately, the purpose of this talk is to inspire a community approach to pushing DIC technology forward.

Digital Image Correlation: Practical Implementation of a 2D Digital Image Correlation Framework as a MATLAB Code

DJ Atkinson–Stellenbosch University; TH Becker–Stellenbosch University

Digital image correlation (DIC) has become a widely adopted technique in experimental solid mechanics for measuring full-field displacements and strains experienced by a specimen. Consequently there are many publications which give a comprehensive breakdown of the mathematical theory of the DIC method; however, these publications do not discuss in detail how the DIC method, that is presented, is implemented in practice as a code. This is detrimental for newcomers to the concept of DIC because the steep learning curve of DIC makes it difficult for these newcomers to obtain a working knowledge of DIC from purely theoretical resources. This paper aims to bridge this gap between the mathematical theory of DIC and its practical implementation by presenting the mathematical theory of a 2D, local DIC framework, that is predominantly consistent with the current state-of-the-art practices, and explaining how this DIC framework is implemented as a practical MATLAB code. This DIC code is then validated by using the SEM 2D-DIC Challenge image sets in order to test its capabilities. The results show that the proposed DIC framework, and subsequent code, determines displacements and strains with sufficient accuracy and precision to be considered reliable enough for use in experimental solid mechanics applications. This paper is to be published in the hope that providing a resource specifically aimed at newcomers to the concept of DIC will encourage these newcomers to get involved in the DIC community by using this code as a starting point to develop their own code..

The Utility of Open Source 2D-DIC Engine Ncorr for Large Compressional Inhomogeneous Deformations in Solid Mechanics

Xiao Cheng Xing–Tsinghua University

This experimental study investigates the utility of the open sourced 2D digital image correlation (DIC) engine Ncorr for establishing the strain field of material specimens undergoing large inhomogeneous deformations. Large inhomogeneous deformations have been observed to occur when porous materials are compressed, which results in high strain values and losses in pixel count during the deformation process. This type of behavior is problematic for traditional DIC methodology, because the initially specified reference image cannot be correlated to the series of highly compressed images due to loss in pixel information. Therefore, the reference image must be incrementally updated as DIC calculations continue. Large compression of a typical porous material have been conducted utilizing the split Hopkinson pressure bar (SHPB) technique, then processed with the open source Ncorr engine and the commercially available Vic-2D software, resulting in the specimen's displacement field. To standardize the strain field between Ncorr and Vic2D, the MaxPol gradient kernel is utilized to calculate the strain field. Lastly, the mean of the strain field is taken to determine the total strain and compared with a reference strain measurement found through DIC tracking of incident and transmitter bars of the SHPB test rig. Good correlation is found between the displacement fields of the Ncorr and Vic-2D results. Good correlation is found between the strain fields of the Ncorr and Vic-2D results. Good correlation is found between SHPB reference strain measurement, mean Ncorr strain and mean Vic-2D strain.

Robust Heuristics-Enabled, Vision-Based Sensing for Road Traffic Artifacts

Milkyas Afework–Oklahoma State University;
James M. Manimala–Oklahoma State University

According to a study by America Traffic Solutions, 719 people die each year; 60 people die each month and $390 million is lost in cost due to red light running. In recent years' autonomous technologies are seeing more and more use in automobiles. While driver assistance technologies are becoming more common in vehicles, the majority of vehicles currently on the road have little or no driver assistance features. In the near future, automobiles on the road will have a spectrum of autonomy ranging from full autonomy to mostly manual vehicles. In such a context, there is a need for efficient yet affordable driver assistance technology that can integrate easily with the existing transportation ecosystem. An approach based on computationally efficient image processing techniques coupled with domain-centric heuristics is investigated to address this need. Specifically, we have created a set of robust heuristics-based algorithms that takes advantage of image processing techniques. These heuristics are extracted by identifying spatial and temporal invariants related to traffic artifacts. They can then be utilized in order to create a vision-based, forward looking early warning system for automobiles that detects and alerts the driver to (i) aspect and context of traffic lights, (ii) traffic signs including stop signs and speed limits, (iii) impending collision with obstacles ahead, and (iv) lane departures. The key innovation is within the robustness and hierarchy of the heuristics and their implementation with a computationally efficient framework. This allows for real-time, on-board detection of traffic lights, signs, impending collisions, and lane departures without the need for external connectivity (WiFi, Data usage or GPS) or complex sensors (only an ordinary dashcam or mobile phone camera is needed). Real-time, road tests of this approach using a prototype dash-mounted device delivered detection refresh rates in excess of 3 times per second and an accuracy of over 80% for traffic light sensing. Besides, traffic sign detection, lane detection, and forward collision avoidance features were integrated into the prototype device using machine learning methods. The computational efficiency and potentially affordable implementation could make this approach promising for other applications such as structural health monitoring and scientific data acquisition.

Characterization of Sheet Formability using Hydraulic Bulge Tests with DIC

Yang Song –University of Windsor; Daniel E. Green–University of Windsor

The accuracy of numerical simulations of sheet metal forming is dependent on the quality of the experimental data used to characterize the sheet mechanical behaviour. The circular hydraulic bulge test is a very good characterization test for sheet materials since it provides a continuously balanced biaxial stress state and a linear strain path up to large deformations and to the onset of fracture. The through-thickness stress acting on the sheet specimen, which invalidates the plane-stress assumption, is uniformly distributed and can be easily accounted for in the determination of the work hardening behaviour. In this work, hydraulic bulge tests were performed on two sheet materials (DP600/AA5182) using digital cameras to continuously record the deformation. Commercial DIC software Vic-3D was used to determine the strain field and strain history across the specimen surface in each test. An advanced method of curvature regression based on DIC measurements was adopted to accurately calculate the instantaneous thickness at the pole of the pressurized specimen. With the help of DIC, accurate work hardening behaviour, forming limits (determined according to the ISO 12004-2:2008 standard) and fracture strain limits were determined in balanced biaxial tension for each of these sheet materials.

Determination of the Forming Limit Curve and Bi-Axial Yield Curve using Digital Image Correlation up to 1200°C

André Grube; Burak Acun; Oliver Witzel; Markus Klein; Thorsten Weikert; Dominik Lilje

In modern sheet metal forming processes the material properties are an important aspect for an successful product manufacturing in the automotive industry and consumer goods industry, as well for the steel and aluminum suppliers. DIC is used in the application area of the Determination of Forming limit curve (FLC) according to ISO 12004 and Bi-axial Yield Curve according to ISO 16808 to provide accurate and reliable material property data. The FLC procedure and evaluation method is standardized in ISO 12004-2. The accurate full field measurement is used to evaluate automatically the forming limit parameter for major strain and minor strain values with the section-based method according to ISO 12004-2 or even time-based method (linear best-fit method). Numerical forming simulations require accurate material parameters as input. An important input parameter is the yielding criteria of sheet metal materials. Therefore the Bulge Test according to ISO 16808 is performed. DIC provides accurate measuring results of the required surface curvature radius and material thickness strains to calculate automatically the bi-axial stress strain curve using Barlow's formula. Modern materials for crash relevant components combine high strength and high formability. These advanced materials are processed in hot forming with temperatures up to 1200 °C. Considering the pattern creation and environmental effects DIC is used to provide the material properties FLC and Yield Curve under this special conditions. Furthermore DIC is used to determine this material properties as well under crash conditions with 300mm/s to simulate the real velocities of actual sheet metal forming presses.

Sheet Metal Formability Characterization under Hot Stamping Conditions

Sante DiCecco –University of Waterloo; Michael Worswick –University of Waterloo; Cliff Butcher–University of Waterloo

Safe and lightweight structural vehicle components are increasingly being designed for high-strength sheet metals that cannot be supported by conventional forming technologies. To accommodate these advanced materials, the hot-stamping (HS) process has been developed for ultrahigh strength steels and the die-quenching (DQ) process has been developed for precipitation-hardening aluminums. Both processes are elevated temperature non-isothermal forming operations that offer excellent formability; however, relatively few studies exist which effectively quantify the aforementioned formability advantages – adding uncertainty to the design process. In the present work, the formability evaluation of a 7000-series aluminum alloy has been completed under DQ conditions using stereoscopic digital image correlation (DIC) techniques in combination with traditional limiting dome height (LDH) Nakazima testing methods. Two specific processes were examined, both beginning with a solutionizing step at 475°C and followed by: (i) an intermediate quench and form (IQF) process in which the LDH coupons were quenched to preset temperatures, and isothermally formed and (ii) a die-quench process where the LDH coupons were quenched and formed simultaneously with room temperature (RT) tooling under non-isothermal conditions. Under these high temperature and large strain conditions, a robust speckling process was iteratively developed to enable in-situ DIC analysis. The best DQ and IQF processes both produced plane strain limit strains in excess of 0.5 major strain, above which an orange-peel defect was observed. For lower IQF temperatures, significant strain striations were observed. The lessons learned from DIC analysis under DQ forming conditions were extended to the HS regime, where different DIC challenges were encountered.

Combination of Scans and Measured 3D Data for the Calculation of Virtual Geometry Elements

Burak Acun; Oliver Witzel; Markus Klein; Thorsten Weikert

The optimization of modern product developments in the automotive industry demands accurate and reliable measuring results available in the shortest possible time. Moreover, measuring results must be user independent and repeatable to meet the challenging requirements of today's product development process in the automotive industry. The dynamic analysis of door, hood and tailgate slam helps to better understand the kinematics. Furthermore, an interesting consideration in such attempts is the vibration of the door panel or the hood. The aim is to avoid contact with the component behind it. In a typical misuse test, e.g. at the door, speeds of up to 3m/s are achieved. A big challenge is the dynamic analysis of the seal. In combination with CAD or scan data, the overlapping area can be displayed dynamically. The analysis of the complex movements in the chassis area and their design are decisive for driving comfort. For example, the actual steering axle can influence the trail angle. Conventional measuring equipment is reaching its limits, but measurement in this area also poses a great challenge for optical metrology. The combination of scan data and the measured 3d points enables the calculation of virtual geometries, which are used for the analysis of the steering angle and trail angle.

An Approach for Dynamic Model Calibration Using Error Localization Algorithms: Demonstration Using Two Practical Examples

Lucas G. Horta–NASA Langley Research Center; Mercedes C. Reaves–NASA Langley Research Center

Model calibration of dynamical systems is a very important activity undertaken for the verification and validation of models for systems under dynamic loads. Calibrated models are used for flight loads assessments and stability analysis. The importance of this task has prompted numerous excellent papers and books on the subject, including the development of commercial programs to automate the calibration process. Unfortunately, at times users have unrealistic expectations about the process and their ability to correct model deficiencies using existing tools. Work here will likely not change this fact, but our hope is for users to understand the process and to establish realistic metrics to assess models from a more practical viewpoint. Moreover, the paper discusses the implementation of three Error Localization Algorithms (ELA), assessment metrics, along with two examples of model calibration efforts. The calibration process relies heavily on collecting data from a modal test. When tests are properly designed and executed, sensors and inputs are placed strategically to extract key target modes. Pretest analysis establishes the number of sensors and number of inputs needed to extract key target modes. These decisions will significantly affect their ability to reconcile models with test. During model reconciliation, users routinely conduct sensitivity studies to determine critical parameters to conduct model adjustments. Although this makes engineering sense, sensitivity information only reflects parameter importance and by itself is not an indication of model deficiencies. Instead, the task of identifying model deficiencies is best suited for ELA in which measured data is used directly to identify potential problem areas in the model. Three ELA methods are applied in this work: 1) Coordinate Modal Assurance Criterion (CoMAC), 2) Robust Model Error (RME), and 3) Analytical Model Improvement (AMI). To establish credibility of the ELA approaches, data from two analytical examples are used with ELA to identify known problem areas. The study considers the effects of insufficient number of sensors and insufficient number of measured modes on results from ELA. Of the three ELA approaches implemented only AMI is able to identify model errors correctly when using analytical models. Using AMI with test data, the model is divided into improvement zones and model parameters in those zones are adjusted using deterministic optimization tools.

Eliminating Mass Effects of Multi-transducers in Vibration Test

Rui Zhu– Southeast University; Qing-guo Fei– Southeast University;
Dong Jiang–Nanjing Forestry University; Zhi-fu Cao–Southeast University

In vibration test of lightweight structures with flexibility, test data is seriously polluted by mass loading effects of transducers. The Sherman-Morrison-Woodbury formula is an efficient mathematical tool for simply representing the change of matrices, on the basis of which, a fast elimination method is proposed to estimate the frequency response functions (FRFs) by removing the effects of transducers. The salient feature of the proposed method is that the effects of multi-transducers can be taken into account simultaneously. Numerical simulation is conducted by employing a six-degree of freedom spring-mass system. Results show that the effects of multi-transducers mass can be removed efficiently and the corrected FRFs are in quite good agreement with the target values.

Damper Experimental and Numerical Correlation

Jason T. Cook–Oak Ridge National Laboratory; Thomas J. Hazelwood–Oak Ridge National Laboratory; Claire R. Luttrell–Oak Ridge National Laboratory; Blake W. Van Hoy–Oak Ridge National Laboratory

The process of characterizing a damper involves both experimental techniques and model simulation. Experiments characterize dynamic behavior of a system through empirical modal analysis using impact and shaker testing. The layout of the test setup is crucial for a low mass nonlinear system. Physical arrangement and orientation of the system and instrumentation affect the results which are discussed in this paper. These results can be used to validate a numerical simulation of the same system. With a validated model, important physical input parameters and modeling techniques can be determined and implemented in future designs. That is to say that modeling can be used with confidence in designing alternative dampers which may be difficult, costly, and time consuming to experimentally characterize.

Studying Feasibility of Applying Digital Image Correlation Algorithms on Infrared Images

C.Casavola; V.Moramarco; G.Pappalettera

Full-field optical methods constitute a valuable class of tools in experimental mechanics which have been applied, in the last decades, to a number of different problems. in the last years, in conjunction with the advancements in computing a new full-field approach is becoming more and more widely adopted. This is the so called Digital Image Correlation (DIC) approach which is, in its essence, based on algorithms of image analysis and comparison allowing to extract information about, shape and strain/displacement field of the object under study. The core of the approach consists in studying the correlation of each sub-portion of the reference image with each sub-portion of the image of the loaded object. This can be conveniently done if a random, isotropic, high-contrast pattern is present on the surface to be analyzed. Such a kind of pattern can be naturally present on the object under analysis or artificially sprayed on it. Also temperature measurements can get great advantages from adopting full-field approaches allows to get the entire temperature field instead of a single average temperature value. It is well known, in fact, that by using infrared (IR) thermography it is possible to evaluate point by point the temperature of a body with a known emissivity by using an infrared detector and a proper collecting lens to record the radiation emitted in the infrared spectrum. In many situations both strain field and temperature field have to be recorded in order to have a full comprehension of the thermo-mechanical behaviour of the analyzed component. For example, in IR thermography and ESPI were used to detect the thermomechanical behaviour of a power transistor. In this paper we study the feasibility of using a simplified approach for measuring displacement/strain field and temperature field at once. This relies on performing digital image correlation analysis directly on thermal images. This would allow, whenever it is possible to prepare to surface with a random pattern of emissivity or when it is naturally present on the sample to analyze, to get in a simple way the complete thermomechanical response of the sample. Implementation of a combined IR-2D DIC system is here shown; a calibration procedure is presented and validated and finally results on a case study are illustrated.

Using Finite Elements as a Means to Interpolate and Extrapolate Local Mechanical Fields from Discrete Experimental Data

D. Roucou–Université Lille, Michelin; J.-F. Witz–Université Lille; M. Brieu–California State University; A. Mbiakop-Ngassa–Michelin

Today, strain fields are often measured using the well established method of DIC. This technique can be extended to large deformations, however due to the potentially extremely different initial and final configurations, approximations in the method can accumulate and give an uncertain result. Another technique proposes to follow the positions of visual markers which allows to know the precise positions of specific material points. Nevertheless, this alternative method presents a difficulty in order to obtain exploitable continuous strain fields: the information obtained is discrete. The data may directly be interpolated to obtain displacement fields, but material boundaries cannot be extrapolated, being outside of the marker grid. Additionally, measurement noise may be present leading to difficulties when the fields are derived to obtain strain. Finally, both the interpolation and derivation may be perturbed by the presence of a geometric singularity such as a crack or a hole. We propose a novel method which allows to lift these issues. A tensile specimen of a hyperelastic material with a central hole has been filmed when stretched unixially. The markers on the surface could be followed using a point tracking algorithm. Then, the inital marker's positions as well as the knowledge of the specimen geometry were used to create a 3D mesh including nodes at each marker's position. The positions measured in the final configuration were used to determine each markers's displacement. Then, finite element simulation was performed on the mesh using these displacements as boundary conditions applied on the corresponding nodes, on one of the mesh faces. Simulations were also performed using only the extremal markers, closest to the clamps. The opposite face was let loose, guided by a symmetry condition in the middle plane. A Mooney-Rivlin hyperelastic law has been adopted and the effect of material parameters on the results are studied. Results show that when the extremal displacements only are applied, the deformed boundaries depend strongly on material parameters. When all the measured displacements are incorporated, it is much less so, showing that the material law has little impact on the obtained deformed configuration. Since the boundaries are not constrained, their agreement with those experimentally filmed are used as validation for the obtained fields, including extrapolation outside of the marker grid.

The Virtual Image Correlation Method: Principle and Uncertainty

MLM François–Université de Nantes; M Baconnais–Université de Nantes

The Virtual Image Correlation method is a silhouette measurement method close to the global DIC. However the second image is, in this case, a virtual one which consists in a simple, unitary, black to white gradient which mimics the border of a silhouette. The field of displacement between the two images is given by a parameterized curve. Once the deformed virtual image is in best correlation with the contour of interest, the curve equation represents a precise measurement of this silhouette. In mechanics, the VIC boundary measurement can be used on specimen or structure. Using it on reference and deformed states lead to measure the (normal) displacement of the boundary. In case of elongated objects or when no mouchetis can be applied, this method can replace the DIC. It is also possible to use the VIC boundary measurement to help the DIC to be more precise close to borders; however this is detailed in another talk. The presented work includes a new simplified formulation of the method. This one at first is used to show that the VIC is exact in 1D. At second it is shown that the method is insensitive to contrast fluctuation and that brightness deviation induces a bias which can be easily corrected thanks to a linear image correction. At last, analytical expressions of the uncertainty are given, one with respect to image noise and one for noiseless cases. The latter corresponds to the ultimate precision of the method, shown to be in N/20L, N being the number of curve parameters and L the curve length. Such precision is far beyond the present edge detection methods. Optimal numerical settings and optimal value of the sole parameter of the method are given.

Discontinuity Detection using Pixel-wise DIC

Victor Couty–Université Lille; Julien Berthe–DMAS, ONERA; Jean-François Witz–Université Lille; Pauline Lecomte-Grosbras–Université Lille; Eric Deletombe–DMAS, ONERA; Mathias Brieu–California State University-Los Angeles

DIC is commonly used to measure displacement and strain fields during mechanical tests. Some algorithms rely on hypothesis, such as kinematic fields following FEM meshes or chosen degrees of freedom whereas some algorithms compute local displacement using block matching. The spatial derivation of the displacement is the strain of the material. When using hypothesis on the fields, assumptions are made on the solution that may lower the objectivity of the result. When using sparse methods, local events may remain undetected. However, unconstrained dense correlation methods have the tendency to return noisy fields. This noise is amplified by the derivation and strain fields are mostly unusable. The presented algorithm is pixel-wise and takes in account the smoothness of the solution, returning much more exploitable results regarding the strain, while keeping a dense measurement. To do so, a smoothness term is added to the residual. This term is a function of the Laplacian of the solution, lowering the noise on the field, but still allowing sharp and local strain variations. It is shown that this method is stable, unlike a posteriori smoothing and still allows high local variation. It is therefore perfectly suited for discontinuity detection. It should be noted that this algorithm is already implemented in OpenCV and fully open-source. Also, computing time has been lowered enough to allow real-time computation of dense strain fields on a conventional computer. The goal of this abstract is to present the metric used by this algorithm, and the potential uses for discontinuity detection on composite materials as a potential tool for damage quantification. This algorithm could also probably be suited for other local strain studies such as crack study, plasticity detection and in-situ strain measurement. This work has been supported by the DGA (Direction Générale de l'Armement) and the "Hauts-de-France" region.

Quantifying Surface Deformation around Small-Scale Indents by Digital Image Correlation

Mengying Liu– –Texas A&M University; Ian McCue–Texas A&M University; Michael J. Demkowicz–Texas A&M University

To accelerate the development of new materials, high-throughput methods of assessing mechanical behavior are required. We demonstrate a method to quantify flow uniformity by integrating small-scale indentation with digital image correlation (DIC). By correlating pre- and post-indentation surface images via DIC, we obtain in-plane strain distributions around the indent area. We apply this method to metal composites synthesized by liquid/solid metal dealloying, and assess the stain partitioning between composite phases. The method we demonstrate is suitable for rapid screening of materials for their propensity to undergo localized deformation.

In-Situ Full Field Out of Plane Displacement and Strain Measurements at the Micro-Scale in Single Reinforcement Composites under Transverse Loading

Ilyass Tabiai–Polytechnique Montréal; Damien Texier; Philippe Bocher; Daniel Therriault; Martin Lévesque

The fiber / matrix inter-facial damage mechanisms of fiber-reinforced composites (FRCs) are investigated for four different composites containing a single fiber or bundle of fibers under transverse load. A laser scanning confocal microscope (LSCM) is used for micro digital image correlation (μDIC) during in-situ quasi-static tests of single-reinforcement dogbone specimens. Three fibers having radically different bonding strength with epoxy in addition to a bundle of about a hundred carbon fibers were tested as reinforcements. For all specimens, damage initiated with fiber debonding at the free surface along the tensile direction. The crack then propagates around the interface while slightly growing along the fiber. The inter-facial crack is shown to grow faster for couples with weak inter-facial bonding. Strong fiber / matrix bonding is shown to stop Mode II transverse inter-facial debonding which significantly delays specimen failure. Analysis of the LSCM micrographs with μDIC is used to provide measurements of displacements, strains, and measure depth during each test. The importance of out of plane displacements in inter-facial debonding is highlighted. Out of plane displacement is shown to play a role in inter-facial crack opening and growth and ought to be considered when studying or modeling damage in FRCs. μDIC is shown to be a promising technique to provide a better understanding of the damage mechanisms at the fiber or bundle scales and to determine inter-facial toughness of a specific fibre / matrix couple in order to perform accurate damage modeling in FRCs. Displacement, strain, and confidence field results for each pixel from each experiment and at each time step are also provided in an extensive data package for detailed comparison with simulation results.

Concurrent, in Situ HR EBSD and DIC on a Three-point Bend IN718 Specimen

S. Poulton–University of Utah; T.J. Ruggles–University of Utah; G.F. Bomarito–University of Utah; J.D. Hochhalter–University of Utah

High fidelity material models require detailed mesoscale information for calibration and development. Recent advances in SEM microscopy make such information readily available. For this project stress is calculated with high resolution electron backscatter diffraction (HR EBSD) and strain is calculated with digital image correlation (DIC). A simple three point bend fixture is used in situ to deform a small Inconel 718 specimen. The fixture exposes an edge face of the specimen for imaging. The face is polished to enable electron backscatter diffraction and an amorphous carbon pattern has been applied for DIC imaging. This amorphous carbon pattern is thin enough not to obstruct backscattered electrons used in diffraction, but may be readily imaged at lower accelerating voltages for DIC. At each loading step electron backscatter patterns are captured and images are taken of the exposed edge of the specimen. Using the captured patterns HR EBSD is used to calculate the relative stress within each grain. The images are used to perform DIC and calculate the strain on the surface of the exposed face. Combining both datasets gives a stress vs. strain curve at every point on the edge of the specimen, which can be used to calibrate a material model without the need to run a finite element simulation.

Nanoimprint Lithography Speckle Patterns for Optical Microscopy DIC

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The accuracy and spatial resolution of DIC measurements are strongly dependent on feature details of the speckle patterns used. Recent developments in the optimization of speckle patterns have led to very specific designs requiring dedicated methods to apply the pattern to a specimen. In the context of optical-microscopy DIC, an application procedure with sub-micrometer precision is required. Unlike other patterning techniques, lithography-based techniques provide the advantage of transferring precise patterns on the sample surface with high control and reproducibility. The method proposed here considers the development of a Nano-Imprint Lithography (NIL) technique to apply an optimized pattern with a high optical contrast on non-flat surfaces. First, an optimized pattern is generated on a master mold by electron beam lithography; later the elastomeric stamp is replicated from the master mold. The developed method is suitable for the pattern generation on non-flat samples, as the flexible stamp can be brought into tight contact with the sample surface. Prior to the pattern transfer, optically transparent UV and thermally curable resist dispensed over the sample surface is mixed with ink to achieve a high optical contrast. The desired structures should have an equal density of black and white contrast, while the feature size is scalable to desired dimensions by varying the pixel size of the pattern generated on the master mold. In this contribution we report on progress made towards establishing a robust pattern application procedure.

Validation Testing of DIC Frequency Domain Tools for Modal Analysis

Tim Schmidt–Trilion Quality Systems; DJ Winterhoff–Trilion Quality Systems; Peter Avitabile–University of Massachusetts Lowell; Chris Niezrecki–University of Massachusetts Lowell; Nicholas A. Valente–University of Massachusetts Lowell; Matthew D. Southwick University of Massachusetts Lowell

Digital image correlation and the related measurement method of point tracking photogrammetry are increasingly being used for structural dynamics and modal analysis applications. Point tracking photogrammetry can be much more computationally efficient than DIC, while still providing many more data points than accelerometers or a scanning laser vibrometer. A sparse array of DIC points can be rapidly computed for vibrational displacements, and a very dense grid is available for strain measurements if desired. The intrinsic output of DIC and point tracking photogrammetry is an animation of the operating deflection shape which is readily visualized, particularly if the out-of-plane displacements are magnified. To extend the usefulness of a combined DIC and point tracking photogrammetry system for modal analysis, single point and full-field FFT tools have been integrated into the software. In this study, the accuracy of the mode shapes is tested, as is the displacement sensitivity, using both DIC patterns and reference point markers. Results are also compared to those obtained by post-processing exported displacement data into traditional tools such as ME'scope. A well-characterized reference standard base upright structure is excited with band-limited noise, resonant frequencies are selected from the frequency response function, and mode shapes are extracted. Modal assurance criteria are determined by comparison to modes with single frequency excitation at each identified resonance. MAC values are also assessed against modes previously obtained with the scanning laser vibrometer. Displacement sensitivity in the frequency domain is determined by gradually reducing the amplitude of single frequency shaker excitation, as well as the g levels of hammer hits, and noting the MAC value of the extracted mode shapes.

Investigation of Bolt Loosening in Super-alloy Thermal Protection System Panel using High-speed Digital Image Correlation

Vinh Tung Le–Konkuk University; N. S. Goo–Konkuk University

Thermal protection system (TPS) panel was designed and fabricated to protect the hypersonic vehicle interiors from the extreme conditions, such as high heat flux, vibrations, and acoustics that can affect the vehicle structure and its payloads. One problem with the TPS is the maintenance cost and inspection time required to ensure that it is in good condition before the next flight. This study examines the method to investigate the damage state of a super-alloy TPS panel through the modal analysis. The experiment is implemented in three conditions to account for good condition, insulation effect, and bolted-joint loosening. In the experiment, the TPS panel was suspended vertically by two fine-nylon cord. The TPS panel was excited by applying an impulse force with an impact hammer in the dynamic testing. Two high-speed cameras based on digital image correlation (DIC) technique were used to record the response of the TPS panel. The response in the time domain was transferred to the frequency domain to get the frequency response function. After filtering and averaging data, the natural frequencies were determined by the peaks of the frequency response function. The first mode of the healthy TPS panel was at 192 Hz while it was 172 Hz for the damaged state at one corner of the TPS panel. Based on changes in natural frequencies and mode shapes due to the TPS failure, the bolt loosening could be detected. As a result, the damage state such as a loose fastener reduces the stiffness of the TPS panel which results in the natural frequencies degradation. The method demonstrated the advantages of the DIC method in measuring the full-field and non-contact deformation of the aerospace structure.

DIC and Digital Twin: An Inescapable Combo for an Efficient Model Validation

Nicolas Swiergiel–ArianeGroup; Florent Mathieu–Eikosim; Pierre Baudoin–Eikosim

In the aerospace industry, earnings of performance associated with gain of time and cost savings are a constant for the development of new products. These constraints imply a perpetual reappraisal of development process. The classic building block approach involves both the testing and the numerical modelling. For the testing, the interest of DIC is an established fact: a large number of articles and presentations show various success stories with DIC measurements. However a few articles show their potential for the model validation and their capacity to create new synergies between the test lab and the design office. Consequently and in the framework of tests on metal/composites junction, it is proposed to illustrate this last point. The importance to develop a specific methodology and especially a software platform allowing an efficient test / simulation dialogue in an industrial environment will be shown.

Benefits of Virtual Testing for Test Validation with Blender

Pierre Baudoin–Eikosim; Clara Minguet–Eikosim; Renaud Gras–Eikosim; Florent Mathieu–Eikosim; Stéphanie Sailly–Mecatest

Designing DIC instrumented experiments in an industrial environment can be challenging. Owing to a combination of large structure scales and component complexity, it can be difficult to anticipate appropriate camera positioning to ensure that the target areas will be and remain visible during testing. Obtaining a priori estimates of measurement uncertainty in these conditions is even more problematic. In the present study, we present some of the advantages of using a 3D rendering software (Blender) with these objectives in mind. This approach is the natural extension of virtual benchmarks on synthetic images commonly performed to estimate 2D DIC software performance. Here, it is further proposed to take advantage of the (usually available) FE model and predicted displacement on the surface of the structure to generate pre-test and post-test images close to those that will be observed in actual experimental conditions (see step-by-step flowchart and illustrations below). This lets us test the influence of many parameters on the measurement feasibility (appropriate camera Field of View and Depth of Field, light position) and accuracy (a priori estimate of smallest measurable strain values, ideal speckle pattern size and camera resolution). The benefits and limitations of this approach to design structural Stereo-DIC tests will be examined, with a special focus on the influence of rendering parameters on the registration quality. We will further present the benefit of a priori measurement uncertainty on test design.

DIC Uncertainty Quantification in Practice

P. Lava–MatchID NV; F. Pierron–University of Southampton; L. Wittevrongel–MatchID NV

In this session, a detailed overview will be presented on how MatchID approaches uncertainty quantification of optical methods in practice, with a particular focus on noise reduction and signal reconstruction. It will be shown how setting up "virtual experiments involving DIC uncertainties" can help to define optimum settings (e.g. subset size, step size, shape function, strain smoothing), optimize real experiments, indicate bias and precision. Results will be presented for various academic and industrial test cases encompassing the entire design chain, including Material identification, Geometry optimization, Model validation.

Simultaneous IR/DIC Measurements for Thermomechanical Modeling

Amanda Jones–Sandia National Laboratories; Elizabeth Jones–Sandia National Laboratories; Ben Reedlunn–Sandia National Laboratories; Sharlotte Kramer–Sandia National Laboratories

This work targeted a full-field understanding of the conversion of plastic work into heat for large deformation metal plasticity using advanced diagnostics (digital image correlation, DIC, combined with infrared, IR, imaging). Tensile 304L stainless steel dog bones are pulled in tension at quasi-static rates until failure and full-field deformation and temperature data are captured, while accounting for thermal losses to the environment. The IR temperature fields are mapped onto the DIC coordinate system (Lagrangian formulation). The resultant fields are used to calculate the Taylor-Quinney coefficient (β) at two strain rates (0.002 s-1 and 0.08 s-1) and two external temperatures (room temperature, RT, and 250°C). The values for the Taylor-Quinney coefficient obtained varied as a function of all three variables explored (strain, strain rate, and external temperature), which follows many literature assertions that the common assumption of a constant value for β is invalid. The sources of error and experimental improvements desired are discussed. Acknowledgements: Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

Simultaneous Surface Deformation and Temperature Measurements Using Digital Image Correlation and Thermographic Phosphors

E.M.C. Jones–Sandia National Laboratories; K.N.G. Hoffmeister–Sandia National Laboratories

Fluid–structure interactions (FSI) are important for many engineering applications, including design of bridges, skyscrapers, airplanes, and spacecraft. The use of digital image correlation (DIC) to measure the structural response of a component subjected to fluid loading has significant advantages over traditional instrumentation such as pressure transducers and accelerometers, since DIC is non-intrusive and provides richer, full-field data. However, optical-based DIC suffers from beam-steering due to imaging through a complex fluid flow with heterogeneous and transient density gradients and index of refraction. Two approaches to overcoming challenges with using DIC for FSI characterization are discussed: optical-based DIC and x-ray-based DIC. For optical DIC, several practical considerations were addressed to realize high-precision measurements, including 1) appropriate camera model and calibration method when viewing the test piece through thick windows; 2) wavelength drift and associated beam-steering from Xenon flash lamp light sources; 3) facility motion and vibrations; 4) aero-optical distortions from shock fronts, vortex shedding, and turbulence. The concept of x-ray DIC was first demonstrated in quasi-static conditions and shown to have comparable accuracy and precision as optical DIC in conditions lacking refractive gradients. In experiments with large refractive distortions, x-ray DIC has been shown to produce superior results to optical DIC. In the present work, stereo x-ray DIC was extended to dynamic events, with imaging rates of 10–20 kHz. Both experimental approaches were applied to an exemplar stainless steel test specimen, composed of a rigid backbone and an outer C-shaped shell, bolted together at internal flanges. The test piece was installed in a shock tube facility and was subjected to an initial impulsive loading from a shock front and subsequent periodic, asymmetric vortex shedding. The goal of the FSI study was to characterize the nonlinear dynamics of the bolted connection, by measuring the motion of the outer flange in situ during the shock tube run. Results from both optical and x-ray DIC will be presented, and the benefits and disadvantages of each technique will be discussed. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC.

Elevated Temperature Optical Microscopy DIC

Kevin Connolly–Southern Research Institute; William Carter Ralph–Southern Research Institute

Digital Image Correlation (DIC) has been demonstrated as an excellent tool to examine the behavior of non-homogenous materials. For this reason, it is regularly used in conjunction with standard mechanical testing to provide high strain resolution. As the innate structure of materials becomes more complicated it can be useful to characterize their micro-scale behavior. Many materials of interest, like composites and 3D printed metals, will have a natural volume element. To understand the material properties, a strain resolution smaller than the unit volume is necessary. Using DIC for these materials is difficult due to the small length scales. Appling strains at small fields of view can most easily be accomplished by heating the specimen to create thermal strain. Conducting DIC while heating a specimen creates an additional set of difficulties for generating quality data. Southern Research has developed a test apparatus and procedures to accomplish this micro DIC testing at elevated temperature. In addition to the apparatus, there will be examples of the future improvements to be made and a description of how the results of the test will be validated.

A New DIC-based Test Method for Characterizing Void Formation in Uncured Autoclave Prepregs

Guillaume Seon–University of Texas at Arlington; Andrew Makeev–University of Texas at Arlington; Brian Shonkwiler–University of Texas at Arlington

High-performance polymeric autoclave composites are increasingly used in the design of aircraft structural components; however, susceptibility to manufacturing irregularities, including voids at ply interface, remains a primary challenge delaying the implementation of advanced composites in modern aircraft. There is strong evidence that improper laminate consolidation at early stages of the laminate manufacturing process, including debulking or vacuum consolidation, is one of the major root causes for defect formation in high-performance autoclave composites. Therefore, understanding and modelling defect formation at these early stages might be the missing link to enable the development of practical engineering solutions allowing for better control of the manufacturing process. In this work, we show how the Digital Image Correlation (DIC) technique can be used in the development of a new test procedure with the objectives to improve our understanding of the physics involved in void formation during vacuum consolidation and allow measurement of key material properties, including the cohesive properties associated with the tackiness of the uncured prepreg material. In the new test setup, air is injected between two plies of uncured prepreg material and DIC is used to monitor the formation of an entrapped air pocket at the interface between the plies, including progression of air-driven fracture.

The Crack-wave Interaction Mechanism in Defected Material Under Impact Loads

Yang Guo–University of Science and Technolo gy Beijing

Combined with high-speed camera, the high-speed digital image correlation technique is established, which can be applied to study the dynamic fracture of media under impact or blast loads. In this paper, the influence of circular hole with different diameter on dynamic crack propagation is studied experimentally. The evolution of strain field between the hole and the dynamic crack is obtained using digital image correlation method. The results show that, when the circular hole is small, the stress concentration around the hole has little influence on the stress field around the crack tip, and the crack will propagate straightly without any deflection. With the diameter of circular hole increases, a significant stress superposition occurred between the crack and the hole, leading the crack gradually deflect from the original path, which first fracturing towards the hole when the crack propagating near to the hole, then fracturing far away from the hole, and eventually recover to its original path after it completely passing through the hole. The strain concentration around hole increases with the increase of holes' diameter. Moreover, when the circular hole is much bigger, the dynamic crack will direct defect its original path and coalesce with the hole. Besides, to further quantitatively analysis the stress concentration of both the dynamic crack and the hole, the stress intensity factor of dynamic crack tip is analyzed. And the results obtained by the digital image correlation method shows a well coincidence with the results obtained by the traditional caustic method, which verify the validity of our results. The results can help us to further understanding the crack-hole interaction problem.

Application of High-Speed Digital Image Correlation to Taylor Impact Testing

Phillip Jannotti–U.S. Army Research Laboratory; Nicholas Lorenzo–U.S. Army Research Laboratory

A methodology is presented using high-speed 3D digital image correlation (DIC) concurrently with Taylor impact testing. Taylor impact experiments are a well-established means of assessing material behavior at high strains and strain rates. Classically, the dynamic strength was determined from the final deformed shape of the sample. However, digital image correlation has been identified as a promising technique to provide time-resolved, full-field characterization of the dynamic failure behavior. This enables a better understanding of the deformation history and can provide a more robust validation of computational models, especially for complex, dynamic problems. In instances where the deformation is multiaxial, especially for non-planar samples, stereo DIC provides one of the only practical means of collecting full-field 3D data. This paper discusses the challenges associated with performing stereo DIC with ultra-high-speed cameras at close to 1:1 magnification. Preliminary results will be presented to demonstrate the utility of instrumented Taylor impact testing. It was determined that ultra-high-speed imaging (greater than 1 Mhz) was required to properly sample the high-rate deformation history occurring over several to 10s of microseconds, despite the impact velocities being on the order of 10s-100s of m/s. Also, for these types of small-scale experiments requiring high-magnification, the narrow DOF (1-2 mm) provided a practical limit on the ability to properly calibrate the stereo DIC system. Lastly, it was found that this type of instrumented high-rate testing holds promise for characterizing a wide range of engineering material (low- to high-strength). Future studies are aimed at performing symmetrical Taylor tests (rod-on-rod) using tungsten carbide (WC) and high-strength steels. These experiments will be used for the development and validation of computational models.

Enhanced Digital Image Correlation with Enforced Traction Continuity Across Interfaces

Yuval Tal–California Institute of Technology; Vito Rubino–California Institute of Technology; Ares Rosakis–California Institute of Technology; Nadia Laupusta–California Institute of Technology

Accurate measurements of displacements around opening or interfacial shear cracks are challenging when digital image correlation (DIC) is used to quantify strain and stress fields around such cracks. The analysis of dynamic quantities associated with propagating ruptures is especially challenging because of the large noise associated with low-resolution ultrahigh-speed photography. Separate correlation on each side of the interface with local approach and large overlapping subsets enables decreasing the noise. However, that requires the extrapolation of displacements from the center of the subset to the interface, which may lead to non-physical discontinuities in the tractions across the interface. This study proposes a simple and fast method to supplement the DIC solution with a post-processing algorithm that enforces the continuity of tractions across interfaces. In the algorithm, the displacements near the interface are extrapolated by local 2-D polynomials that are constructed using a constrained inversion. This inversion is such that the traction continuity conditions are satisfied at the interface while simultaneously matching the displacements produced by the DIC solution at the pixels closest to the center of the subset, where the DIC fields are more accurate. We apply the algorithm to displacement fields of experimental shear ruptures, obtained using a combination of ultrahigh-speed photography and local DIC approach, and show that the algorithm produces the desired continuous traction field across the interface. A sensitivity study provides a constraint on different geometrical parameters involved in the construction of the polynomials, such that undesired artifacts in the stress field are eliminated.

3D DIC Evaluation of Musculoskeletal Soft Tissue: Advantages and Challenges

Alexander W Hooke–Mayo Clinic; Christopher V Nagelli–Mayo Clinic; Christopher H Evans–Mayo Clinic; Sebastian A Mueller–Mayo Clinic, University of Basel, Switzerland

While the role of 3D digital image correlation (DIC) has expanded in the analysis of biological tissues to better understand their complex inhomogeneous, anisotropic, and non-linear properties, its applications to tendon and ligament mechanics have been limited. This may be due to both simplistic generalizations that mechanical response of these tissues is longitudinal and one-dimensional, and the challenges associated with getting robust, high-quality 3D DIC data. Our use of 3D DIC to study tendon and ligament has led to greater understanding of their multi-dimensional behavior while overcoming various specimen preparation challenges. The use of spray paint has been demonstrated to create adequate speckle patterns for DIC. However, this is ineffective in creating a solid, contrasting background on connective tissue as it produces a shell which deforms less than the tissue and cracks, causing gaps in the pattern. Use of a mineral oil-based makeup as a white background has been shown to be effective at deforming with the tissue. Two potentially effective alternatives we have had success with include staining the tissue a dark color with white, spray painted speckles and spray-painting fluorescent speckles on naked tissue. 3D DIC enables the study of 3 primary mechanical measures of musculoskeletal tissue mechanics: 1) the strain's distribution across the tissue, 2) the relationship between deformation and failure locations, and 3) the directional relationship between load and deformation. Each of these three areas is exemplified in the example of the human Achilles tendon being loaded to failure. The distribution of the major strain is non-uniform and varies by ~20% at the moment before failure. The greatest strain occurs away from the site of failure with a localized strain peak at the failure site occurring only just prior to rupture. The direction of the major strain in a majority of the tissue is not parallel to the loading direction. Independent examinations of the transverse and longitudinal strain indicate that the tissue counterintuitively becomes thicker when stretched, indicating it is an auxetic material. Similar breakdowns of the multidimensional deformation behavior of other musculoskeletal tissues have been performed, including other tendons and the 4 primary knee ligaments.

Portable DIC for Dolphin Skin *in-Vivo* Measurement under Vacuum Loading

Dory Ya-Yu Yang–University of Michigan Ann Arbor;
Michael Moore–Marine Mammal Center, Woods Hole Oceanographic Institution;
K. Alex Shorter–University of Michigan Ann Arbor

Bio-logging tags that enable behavioral studies of cetacean are often secured using suction cups to minimize impacts to the animals. However, attachment performance of suction cups is dependent on the material properties and the dynamic response of the skin tissue at the attachment site under vacuum loading. Cetacean tissue consists of layers of skin, blubber, fat, and muscle. The unevenly distributed tissue layers result in a nonhomogeneous hyper-viscoelastic composite with properties that are dependent on the underlying anatomy and exhibits a nonlinear stress-strain relationship under loading. Currently, methods to characterize cetacean tissue under vacuum loading is lacking, and the investigation of suction cup mechanics tend to be limited to their performance on rigid substrates. The goal of this research is to characterize and quantify the response of the composite tissue under vacuum loading, creating new knowledge that can be used to inform suction cup design for bio-logging tags. Here we present a portable digital image correlation (Portable DIC, PDIC) system as well as the methodology to apply waterproof speckle patterns on skin to realize in-vivo full-field measurement of the tissue under vacuum loading. The PDIC system is composed of a semi-transparent hemisphere vacuum chamber with a circular sealing lip, two cameras, nineteen LED lighting units, a vacuum pump, a solenoid valve, and using a micro-controller to apply desired vacuum loading profiles to the skin and trigger the cameras to take a sequence of images simultaneously. The PDIC system was used to successfully measure tissue response from a dolphin cadaver under static step loading and sinusoidal loading. The full-field deformation of the skin was reconstructed, and the peak deformation values were extracted. The results from this work will lead to a better understanding of cetacean skin and facilitate design of suction cups for bio-logging tags.

Digital Image Correlation Analysis of Dental Implant Insertion

Baixuan Yang–Queen's University, Canada, University of Wisconsin-Madison;
Ainara Irastorza Landa–Nobel Biocare Services AG; Peter Heuberger–Nobel Biocare Services AG;
Heidi-Lynn Ploeg–Queen's University, Canada, University of Wisconsin-Madison

Insertion of dental implant strongly affects and associates with secondary stability and success rates of dental implants. It is unclear how the bone is loaded during insertion. However, strain distribution is crucial in order to understand the mechanics of insertion. The objective of this study was to understand the strain field of a bone surrogate during implant insertion. Implants (NobelActive NP 3.5 x 13 mm, Nobel Biocare AB, Göteborg, Sweden) were inserted into bone surrogate (20 PCF, Sawbones® 1522-03) blocks (40 mm x 40 mm x 8 mm) under controlled angular and axial displacement rates using a mechanical testing machine (TA Electroforce 3230-AT Series III, New Castle, DE). Three-dimensional digital image correlation (DIC) was performed to measure deformation on the surface of the bone surrogate blocks during the test (Figure 1). Bone surrogate blocks were painted using an ink stamp with a random black speckle pattern provided by Correlation Solutions. Images were captured at each second using two Grasshopper GRAS-50S5M cameras with a 35 mm focal length lenses (Point Grey Research, Richmond, BC, Canada). Strain field was calculated using image correlation software (VIC-3D, Correlated Solutions, Inc, Irmo, South Carolina). The strain resolution was 500 micro strain. Distribution of first principal strain is shown in Figure 2. Digital Image Correlation provides a feasible tool to determine the strain distribution in the dental implant-bone system.

Fracture Mechanisms of Human Femoral Cortical Bone as a Function of Loading Rate

Tusit Weerasooriya–CCDC Army Research Laboratory;
C. Allan Gunnarsson–CCDC Army Research Laboratory

Blast and impact events regularly cause damage to human tissues. Efforts to improve protective equipment are made through numerical simulation of these events where human tissues experience high-rate loading conditions. Accurate simulation results are obtained when the underlying constitutive models are based on valid material models obtained via precise experimental studies. Experimental studies on bone are challenging because of the heterogeneity, anisotropy and complex microstructure present in bone, as well as its brittle nature. In addition, the mechanical properties of bone change depending on its environmental conditions, such as donor age, hydration, etc. In this study, the rate dependent fracture response of transversely isotropic wet human cortical femur bones from three donors was investigated at different loading rates by measuring deformation in situ using DIC. The initiation fracture properties of cortical bone were studied transverse to the longitudinal axis of the bone using four-point bend experiments at quasi-static, intermediate, and dynamic stress intensity factor rates (0.0143, 15.1 and 45,000 MPa. m½.s-1, respectively), while measuring the full-field deformation around the crack-tip during loading to fracture. The critical tensile strain to fracture initiation was obtained as a function of loading rate and is shown in figure 1. In addition, the measured full-field deformation profiles were used to obtain the KI (Mode 1, tensile) and KII (Mode 2, shear) fracture components as a function of time during loading up to crack initiation. These critical fracture parameters were used to generate fracture mode mechanisms maps (Figure 2a-2c) at different loading rates, by identifying the domains (KI, KII) for the different fracture modes at each loading rate. For each loading rate, a KI threshold was identified below which cracks did not initiate; this KI threshold increases and then decreases as the loading rate is increased. At low and intermediate rates, the dominant mode of crack initiation was either Mode 2 or mixed Mode; whereas for high loading rate, crack initiation was entirely mixed Mode. There was a KII threshold for Mode 2 crack initiation for both low and intermediate rates of loading, and the magnitude of this threshold increased with loading rate. These thresholds can be incorporated into numerical computational techniques so that during simulation, different stress states initiate different modes of fracture.

A New Approach to Experimental Fracture Analysis of High-toughness Films

Jevan Furmanski–ExxonMobil Corporate Strategic Research

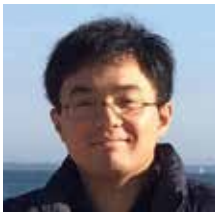
A critical performance characteristic of polyethylene films is tearing resistance. Tougher PE films permit downgauging (use of thinner films for the same application) which is desirable for both economical and ecological reasons. Resistance to tearing is industrially assessed primarily by internationally standardized methods of blunt dart drop impact and high-rate Elmendorf trouser tearing, both of which can be shown to give inaccurate results on some high toughness films. The primary limitation of these standardized tests is their complexity – they are potentially strongly affected by extrinsic effects (such as friction, boundary conditions, and adiabatic self-heating), complicating their use for material design. To address the need for an intrinsic, mechanistically interpretable fracture mechanics test method, a digital image correlation postprocessing framework was developed. This tool utilizes a library of advanced hyperelastic-viscoplastic polymer constitutive models and applies a suitably calibrated model to convert the full-field strain history to stress and energy density fields, which can be mathematically operated on. This permits computation of fracture mechanical quantities, such as the J-integral, but also the more rigorously appropriate thermodynamic fracture driving force derived from Eshelby's momentum-energy tensor field. Finally, with calculated (approximated) stress and energy density fields, interpretation of the material cause of the relative performance of films is facilitated.

Optimized Stereo Digital Image Correlation Setup for Miniature Round Specimen

Farhan Rahman–North Carolina State University; Gracious Ngaile–North Carolina State University; Tasnim Hassan–North Carolina State University

For advancement of micro- and nano-technologies, multiaxial material testing at small length scale is imperative. A novel mulitaxial miniature testing system (MMTS) is under development for testing tubular specimen of outer diameter (OD) as small as 1 mm. 3D Digital Image Correlation (DIC) is the preferred strain measurement method for MMTS. Although theoretically DIC is length scale independent, it has experimental setup related challenges which have contributed against its wider adoption. For the same reason, despite 3D DIC is strongly recommended over 2D DIC, researchers are sometimes compelled to use the later. It is shown in present study that the experimental setup related difficulty, particularly for miniature testing, can be overcome by a systematic development of an optimization framework. This framework addresses all setup variables as well as DIC analysis parameters. Using this framework, a 3D DIC setup was built for testing 1 mm OD specimen with MMTS. Comparison of material properties, derived from miniature tensile and torsion tests performed with developed 3D DIC setup and MMTS, with known material properties, have confirmed the successful development of 3D DIC setup for MMTS. The developed general framework, where the different setup decisions are treated as variables, is intended to contribute in replacing the usual iterative-approach of 3D DIC setup for its wider adoption.

Identification and Validation of 3D Viscoelastic Parameters of Polymer Using Digital Image Correlation



Lingyu Yue–Polytechnique Montréal; Jonathan Jalbert–Polytechnique Montréal; Marie-Claude Heuzey–Polytechnique Montréal; Martin Lévesque–Polytechnique Montréal

The Prony series model, referring to Generalized Maxwell Model in one dimension, is the most used linear viscoelastic constitutive model. Identification of parameters of Prony series models, especially the tri-dimensional model, is one of essential problems of polymeric materials developments and applications. This problem is ill-posed, i.e. the results are not uniquely assured and small perturbations in the data could induce significant variations in the identified parameters, and therefore has been attracted lots of attentions. The objective of this paper is to identify and validate 3D Prony series viscoelastic parameters using Digital Image Correlation (DIC). Two groups of mechanical experiments have been performed in the current study, which are a) creep-recovery experiments on standard ASTM Type I specimens to characterize the viscoelastic properties of polymers, and b) experiments containing complex loading schemes on complex geometry specimens to validate results. DIC permits simultaneous measuring the axial and transverse strain of the deformed specimen in-situ experiments. Therefore, the 3D viscoelastic parameters, i.e. the bulk and shear compliance and their associated characteristic times, can be independently identified from the DIC measurements. A statistical method has been proposed to eliminate the inherent ill-posedness of this identification problem and to determine the optimal number of parameters. This method is based on Bayesian inference and the assumption that DIC measurements errors have a Gaussian distribution. The proposed method has been applied to two polymer materials, Poly(methyl methacrylate) (PMMA) and Polypropylene (PP). The numerical results implemented by the previously identified parameters have good agreement with creep-recovery experiments. Moreover, identified parameters have been validated by experiments performed on specimens with complex geometry. The strain fields measured by DIC and simulated by Finite Element Method (FEM) with identified parameters show a good match. The numerical results obtained were experimentally validated for both the PMMA and PP specimens. The optimal 3D viscoelastic parameters can be identified from DIC measurement using the proposed method. However, the efficiency of this method needs to be improved.

Investigation of Shear and Fracture Properties of Fiber-Reinforced Composite Laminates using DIC

Matthias Merzkirch–National Institute of Standards and Technology

For the analytical description of fiber reinforced polymer (FRP) composite laminates, the intralaminar (in-plane) and interlaminar (through thickness) strength and strain values, as well as moduli are needed. More than a dozen measurement techniques exist for the determination shear properties, several of which are supported by ASTM or ISO standards. One reason for so many attempts is the difficulty in obtaining a reasonably pure and uniform shear stress state in the test specimen. Typically, linear strain gauges and rosette strain gauges are recommended by standards to measure deformations for the determination of the in-plane elastic modulus and the strain to failure. The advent of optical strain measurement techniques such as digital image correlation (DIC), provide new opportunities to generate high resolution maps of the shear strain field as a function of the globally applied strain. DIC allows for the easy full-field mapping of the deformations (in-plane and out-of-plane for stereo DIC) and strains (normal and shear), revealing the pattern of deformation and damage throughout the specimen. In this comparative study, in-plane testing of standardized V-notched specimens and non-standardized 10° off-axis coupons will be compared in terms of intralaminar shear moduli and shear strengths. Additionally, the interlaminar properties determined via standardized 3pt short beam, non-standardized 4pt and standardized 5pt flexural testing will be compared, requiring small span-length to thickness ratios for the shear loading to become dominant. The latter test methods are limited to a determination of the apparent interlaminar strength, while the full stress-strain behavior cannot be determined. The novelty includes the use of the DIC determined shear strains within the elastic loading range to evaluate the shear modulus. The 5pt test allows for a calculation of the shear modulus, provided that four additional elastic, in-plane properties have been determined in advance. Besides material properties such as modulus and strength, also fracture toughness values are needed as input data for cohesive zone models for computational material science purposes. DIC will be used for standardized fracture testing of FRP under Mode I and Mode II (including a comparison of two types of standardized tests) loading conditions, revealing the critical strains as well as crack tip opening displacements in the vicinity of the crack tip as useful data for numerical models.

Toward Quantitative High Resolution Ultra-High Speed Imaging

Adrien Vinel–Université de Nantes, DMAS, ONERA; Julien Réthoré–Université de Nantes; Rian Seghir–Université de Nantes; Julien Berthe–DMAS, ONERA; Gérald Portemont–DMAS, ONERA

Materials may be exposed to high strain rate events in several occasions: e.g. crash, magnetic pulse forming. When submitted to these conditions, transient and heterogeneous phenomena may appear within the material such as adiabatic shear bands. Hence, to have a clear understanding of these complex phenomena, high spatial and temporal resolutions are needed as well as a significant number of images. To this day, recent mono-sensor cameras close to these specifications still do not reach 1 Mpix resolution. To our knowledge, only multi-sensor technologies such as rotating mirror cameras are potentially able to overcome such limitations. However, the complex optical apparatus used to reach these specifications - i.e. multiple independent sensors, combinations of various lenses as well as a mirror rotating at a very high speed - induces non negligible, complex and optical path sensitive distortions. In that context, the use of these technologies strongly depends on our ability to dissociate the optical distortions from the mechanical contributions in the recorded images. The objective of this work is to propose a general route for rotating mirror camera calibration. It is then applied to the ultra-high speed Cordin 580 camera which allows to record 78 - 8 Mpix images up to 4 Mfps. The proposed methodology relies on the use of DIC. Using a synthetic reference image, the modelling of the distortions with polynomial basis can be achieved and effective displacements recovered with a subpixel precision. Finally, this procedure is applied to a dynamic experiment similar to the Kalthoff fracture tests.

Image-Based Stress Reconstruction: A Step Toward a Contactless Dynamic Probing Test

R. Seghir–Université de Nantes; F. Pierron– University of Southampton; J. Rethore–Université de Nantes; L. Fletcher– University of Southampton; A. Vinel–Université de Nantes

In many instances in life, materials around or within us suffer deformation at high rates. This is the case when engineering structures undergo impact, crash, blast, forming etc. Characterizing and accurately modelling materials and/or structures subjected to high deformation rates is therefore crucial. Nevertheless, the transience and the in-homogeneous nature of such loading make both: the experimental capture of the mechanical response very challenging but also make all the potential assumptions regarding the constitutive relation of the deforming material extremely hazardous. Indeed, while a significantly time-dependent material transforms immediately, in the presence of transient dynamic loading, in a complex and constantly changing composite, some polycrystalline materials will undergo for instance strong wave-structure interactions, strain localization, high dissipation thus local softening, dynamic recrystallization etc. Such multi-scale and multi-physic problem would require the development of in-situ material response probing techniques during extreme loading conditions. We demonstrate in the following contribution that experimental full-field measurements of accelerations can be directly used to inverse the local equilibrium equation and reconstruct fields of stress tensor with no assumption on the constitutive relation and its potential spatial and temporal variations. Spatially and temporally resolved displacement fields are obtained using ultra-high speed imaging and image registration techniques while strain and acceleration fields are subsequently obtained by spatial and double temporal differentiation. The methodology is firstly validated on simulated data then applied to an instrumented impact test. It is also demonstrated that both experimental stress and strain fields can be recombined to eventually identified the local tangent mechanical property tensor of the material. The latest constitute a first step in what could be named as "true model identification", as opposed to parameters' model identification.

Simultaneous Comparison of High Speed Digital Image Correlation and Polarization Imaging

Ryan Shannon–InnoSolve

Full-field strain measurement is one reason high speed Digital Image Correlation (DIC) is used in impact testing. However, standard DIC technology is limited to only measure surface strains. Transmission polarization imaging is an alternative full-field measurement technique that can measure integrated stress through the thickness of a transparent specimen. This paper compares DIC and transmission polarization imaging in transparent specimens that are subjected to impulsive loading. The comparison is made simultaneously by speckling half the specimen for DIC while leaving half the specimen clear for transmission polarization imaging. The hardware implemented is this study includes two Photron AX200 cameras for DIC and one Photron Crystal camera for polarization imaging. Photron AX200 and Photron Crystal cameras share common sensor hardware. For example each camera features a 20um sensor grid size. This commonality eliminates variables in this test setup. The results of this simultaneous study will provide the reader with greater insight into the differences between these two full-field measurement approaches.

Combination of Point- and Surface-Based DIC Measurements with Computed Tomography Data

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Biomechanics place huge challenges on existing measurement technologies for determining the mechanical properties of materials, as well as verifying parts performance, such as implants. Shoulder dislocation is the most common dislocation e.g. caused by an accident (traumatic dislocation) or constitutional (habitual dislocation). Consequences are restriction of the mobility of the shoulder's joint or painful and changed shoulder form. Various fixation methods have an influence on the stability. The commonly used Latarjet Procedure and other fixation methods were analyzed by digital image correlation methods. Even complex movements such as those of individual vertebrae can be analyzed in detail with point- and surface-based DIC to get the relative six degrees of freedom (6DoF) movement. These experiments help to understand the movement of an intact spine column and makes it possible to analyze the comparison between an intact spinal segment and a spine segment stabilized by a cage after surgery. A further advantage with the help of motion analysis is to use the computed tomography generated data for the dynamic determination of intervertebral disc thickness change.

Hybrid Experimental-Modeling-Computational (HEMC) Methods: Validation of Microstructurally Inspired Deformation and Failure Models of Human Skull

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The complex structural arrangement of bone within the skull challenges the use of biofidelic finer finite element (FE) meshes representing the complex microstructure. At the extreme of simplification, representation by courser homogenous meshes of the skull may be inaccurate due to the lack of conclusively validated models of material deformation and failure that incorporate the microstructural details of the bone. Additionally, the failure initiation and propagation cannot be precisely captured with a coarser (homogeneous) representation of the skull. Power laws relating the modulus and failure of adult human skull to the morphology, specifically the bone volume fraction (BVF), have recently been developed at the US Army Research Laboratory (ARL) and the University of Virginia (UVA), for compressive and tensile responses of the skull, respectively. Both were derived from measurements of the non-uniform surface deformation profiles enabled by digital image correlation (DIC). Here, the ability of the power laws from ARL to simulate a quasi-static fully instrumented experiment with measured full-field deformation of a 3D skull bone coupon compressed to failure was evaluated by assuming that the deviation from linearity in load-displacement is due to progressive failure of elements, starting with highly porous trabeculae. Ignoring the existence of the complex network of pores, thus enormously simplifying the complex meshing process, a FE mesh based only on the outer geometry of the specimen was used. Elements represented a mixture of both bone and pores, with the corresponding bone material deformation and failure models scaled accordingly. A method was developed to calculate the BVF of each element by identifying the the physical volume represented by the element within the previously measured BVF map of the specimen. Then, each element was assigned mechanical properties using the modulus-BVF and strength-BVF relationships that were obtained experimentally at ARL. The meshing method, combined with the morphology-based mechanical properties, was able to replicate the initial linear portion as well as the subsequent non-linearity of the experimental response before failure (or complete loss of capacity to resist force), as confirmed by the measured stiffness and by comparison of the DIC measured two-dimensional strain fields and failure over the specimen faces.

Global Stereo-DIC based on Finite Elements for the Identification of the Parameters of a Constitutive Law

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Stereo Digital Image Correlation (S-DIC) is increasingly used in experimental mechanics. The recent development of a global S-DIC formalism, based on finite element meshes, allows to measure a 3D-kinematic field directly in the world coordinate system. A benefit of this method is that the experimental measurement is expressed in the same discretization support than the simulation; which greatly facilitates the dialogue between experiments and numerical simulations. The main goal of this study is to develop a method for the identification of the material properties from global S-DIC measurements. For this purpose, a calibration method of the parameters of a non-linear camera model has been proposed, as well as a shape measurement method. Thus, an experimental 3D field, of the sample surfaces is obtained. This calibration step is fully realized in the global S-DIC formalism. Moreover regularization techniques can be implemented in order to approach a result that is physically sound. Thanks to the use of the same finite element mesh for the measurement and the simulation, it is possible to compare directly the experimental and computed kinematics fields. Thus, algorithms can use this property in order to identify the parameters of a constitutive law for the considered material. It is the case for instance of the well-known Finite Element Model Updating (FEMU) algorithm. The aim of "FEMU"-like algorithms is to update the value of the parameters such as the result of a numerical simulation, computed with appropriate boundary conditions, is as close as possible to the kinematic measurement, within the meaning of a given norm. This methodology is applied to the identification of the elastoplastic law of an open-hole steel plate.

Stereo Digital Image Correlation on Vibrating Materials for Damage Detection

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Mode shaping is a technique done to detect structural damage of a material via vibrations. Previous techniques to measuring materials discontinuity have been done by with point by point laser scans and more recently Laser Doppler Vibrometer (LDV). Using two high-speed cameras to do 3 dimensional stereo Digital Image Correlation (3DDIC) can give time-resolved full-field measurements that can track displacements, frequencies and modes of vibrations in experiments lasting seconds versus hours. DIC involves randomly speckling a sample with white paint and a permanent black marker and tracking the motion / deformation of the speckle pattern. The speckled bar is attached to a shaker on one end and a pivot on the other, the shaker is set to a known frequency and the vibrating bar is recorded with a high speed stereo camera system. This experiment will compare different frequency responses at different frame rates. Continued experimentation can be used to show the modal discontinuity on vibrating rod because of hidden damage. Using this DIC technique, there is a bar with damage on the back face in a known shape, depth and, location. The bar was tested at five different frequencies and at different frame rates. During post processing of the data line profiles of the out of plane displacement are taken and analyzed. Figure 1 Shows the out of plane displacement in mm overlaid onto the bar caused by the modal excitation shaker at 67 Hz in six consecutive frames. And Figure 2 Shows the out of plane displacement line profiles from Figure1

Non-Parametric Correction to History Dependent Material Constitutive Laws from Displacement Field Measurements

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Using the opportunity of measuring a full displacement field has been exploited in the past decade to design efficient and robust inverse methods. The aim is to obtain the parameters of a presupposed constitutive law that minimize a cost function invoking the rich-data map from DIC. While the proposed inverse methods were shown to be robust and efficient, the constitutive law by itself becomes the weak point of the methodology. Constitutive laws are usually elaborated based on very simple material test what make their prediction, even for optimized parameters, pure extrapolation. In this contribution, we propose to start from a Finite Element Model Updating strategy using a presupposed constitutive equation. Then, a non-parametric strategy is elaborated in order to obtain a non-parametric correction to the response of the presupposed model. This strategy ensures that: the strain field is the one measured by DIC and the stress field satisfies the balance of momentum equation and balances external loads. The material state database that is subsequently identified can be used in so-called data-driven computational analysis. The ability of the proposed methodology to extract material database from complex experimental tests will be illustrated. We will focus on the analysis of materials which behavior depends on the loading history. Therefor a specimen, made of mild steel, with two holes inducing stress/strain heterogeneity and multi-axiality. The sensitivity of the elasto-plastic behavior to strain rate is clearly evidenced.

A Fast GPU-Based FFT Interpolant Algorithm for Synthetic Image and Volume Deformation

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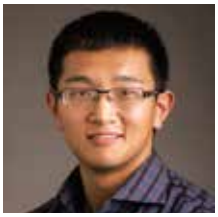
Digital Volume Correlation (DVC), the 3D extension of Digital Image Correlation (DIC), is a motion and deformation metrology method for rendered volumes. Quantitative error analysis is important, especially for code validation in custom DVC implementations. Variation in scan quality, and motion control precision between multiple X-Ray CT systems necessitates the development of numerical deformations to evaluate the accuracy of DVC codes [1]. Many interpolation schemes are computationally expensive, on the order of minutes per image necessitating an optimized algorithm to numerically deform high-resolution CT volumes composed of thousands of slices. A high-speed Fourier-based numerical deformation scheme will be derived and implemented in this paper to provide a set of reference images with known displacements and strains to evaluate the accuracy of DVC.

Fast Adaptive Augmented Lagrangian Digital Volume Correlation



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Digital volume correlation (DVC) is a powerful experimental method to measure three dimensional body volume deformation by tracking 3D stack digital images. Most current DVC algorithms can be categorized into local and finite element based global methods. However, there are some drawbacks in these methods. In local method, since all the local subvolumes are solved independently, the computed displacement field may not be compatible, and the deformation gradients can be very noisy, especially when the subvolume size is small. Global method incorporates kinematic compatibility but can be computational expensive. Here we report a new global DVC algorithm, the augmented Lagrangian digital volume correlation (ALDVC), that combines the advantages of both the local (fast) and global (compatible) methods. It builds on our recent work on the augmented Lagrangian digital image correlation (2D-ALDIC) and solved using the alternating direction method of multipliers (ADMM) scheme. We demonstrate that ALDVC has higher accuracy and behaves more robustly compared to both current local and global DVC methods. Nowadays, FE-based global DVC experimental measurements can be combined with finite element numerical simulations at the same time. However besides expensive computation cost, it is also difficult directly apply an adaptive finite element mesh where (DVC-)stiffness matrix and external force vector have to be rebuilt every time the mesh is changed. Instead we demonstrate that ALDVC can be implemented with adaptive mesh efficiently, which could save computation time one order of magnitude with almost no loss (and maybe some gain) in accuracy.

Internal Full Field Strain Measurement of Composites Material using X-ray Digital Radiography and Digital Image Correlation Techniques

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The National Institute for Aviation Research (NIAR) at Wichita State University (WSU) developed a methodology to measure internal strains and displacements of composite structures under mechanical loading by utilizing X-Ray Digital Radiography (DR) and existing digital image correlation (DIC) software (ARAMIS and VIC-3D) . Surface full field strain and displacement measurement techniques are sufficiently matured to be confidently used in experimental evaluations and correlate well with Finite Element Analysis (FEM) results. However, the techniques currently available to measure full field internal strains and displacement are under development. For this research program, NIAR researched on embedding X-Ray sensitive materials inside different layers of the composites structure during the fabrication process. The size and arrangement of this material was selected based on preliminary experiments to mimic a random speckle pattern required by DIC techniques. After the fabrication process, Open Hole Tension (OHT) specimens were extracted with X-ray sensitive material in selected layers. The specimens were mechanical loaded using a custom designed load frame that is mounted inside the X-ray system. X-Ray DR images were acquired at different load levels and analyzed using the DIC software. Parallel to the experimental activities, the research team developed Hi-Fidelity Finite Element (FE) models to extract the internal strains and displacements at selected ply interfaces. The experimental and analytical results showed good correlation. With this technique, experiments can be conducted to understand how the interaction of strains at different ply interfaces contribute to the overall damage initiation and propagation mechanisms of composites structures. Additionally, experiments were designed to evaluate the effects of the embedded particles on mechanical property response of the material. Static tests were performed to evaluate the effect and showed minimal effect on the material properties. Future research of this program include making modifications to the current X-ray setup to acquire 3D images of the structure to measure out of plane displacement response at different ply interfaces.

A Rotating Specimen Load Frame for CT Scanner and DVC

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X-ray tomography scans can be used for Digital Volume Correlation (DVC), revealing internal damage build-up and crack initiation sites in mechanical loading. To maximize spatial resolution in CT scanners without lensing, the X-ray source must be placed less than 10mm from specimen, complicating specimen design. A common load frame design implements a polymer tube support structure. The tube is thin and relatively transparent to the X-rays. The entire frame is then rotated on the existing CT scanner turntable. This approach simplifies integration into the CT scanner. However, the tubular support 1/complicates specimen loading, 2/increases the distance between source and specimen substantially beyond the high resolution limit, and 3/blocks some of the X-rays, which is particularly problematic for polymeric samples. The polymer tube is also prone to creep during the scan. The proposed solution implements two steel posts and three co-axial servo actuators to rotate the load train within the frame. As such, the source can be placed very close to the specimen The coaxial design limits out of plane motion during the scan and can be configured as an axial plus torsion load frame. Grips have been designed to clear the X-ray tube geometry. This functionality posed alignment challenges. Results from the first installation are presented.

Evaluation of Tensile Properties of Transversely Isotropic Rocks Using Brazilian Disc Test and Digital Image Correlation

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Indirect tensile test using Brazilian disc test (BDT) is widely used in rock characterization because of the ease of preparing cylindrical disc specimens and simple loading setup. However, the analysis of the results from BDT is complex when the specimen is not isotropic. In this study, 3D-digital image correlation (DIC) system is incorporated during BDT to capture and characterize the complex full field deformation of rock samples from two hydrocarbon producing formations (Berea sandstone and Mancos shale). Variation of failure load, displacement and strain fields and final fracture pattern induced by testing are examined as a function of the orientation of bedding planes with loading axis. The validity of strain measurement from DIC on porous rock samples is ensured by mounting strain gages on back-face of specimen and comparing strain values obtained using the two methods. Based on the strain obtained from DIC analysis, the five elastic constants for the transversely isotropic model of the tested rocks are also determined. The fracture patterns and strain fields at fracture locations are utilized to determine the nature of induced fracture (tensile or shear). The specimens show higher strength when bedding planes are perpendicular to the loading axis with tensile fractures occurring at peak load. This study provides the tensile elastic properties which can be used for hydraulic fracturing treatment design and rock mechanics application.

Estimation of Geo-material Deformation and Strain using Finite Element Based DIC and Smooth Particle Hydrodynamics (SPH)

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Rock is a naturally occurring material which is discontinuous, inhomogeneous, anisotropy, non-elastic. Knowledge of rock deformation during the failure process is very crucial input required by the mining and geotechnical engineers to design structures in the rock mass. Finite element based global DIC method coupled with smooth particle hydrodynamics (SPH) is developed and implemented to obtain deformation and strain fields on the surface of the sample under the load. This algorithm is applied to monitor and analyse the failure process of cube samples made with artificial rock material. The results show that the DIC algorithm can predict the area of strain accumulation and crack propagation on the surface well ahead of its visible fractures and cracks on the surface. The research demonstrates that DIC is an effective technique for monitoring deformation in rocks, and can provide new insights into the failure mechanism and internal structure of geo-material.

Evaluation of Fracture Toughness of Laminated Rocks using Digital Image Correlation

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Hydraulic fracturing is essential for efficient production from unconventional reservoirs. Most of the unconventional reservoirs in the world consist of laminated rocks like shales and tight sandstones. Fracture toughness is one of the critical factors controlling induced fracture growth which determines the success of fracking operation. In this paper, digital image correlation (DIC) is utilized to determine fracture toughness of sedimentary rocks by conducting a Mode I semicircular bend test (SCB). Samples were taken from outcrops of both homogeneous formations (Parker Sandstone) and vertical transverse isotropic formations (Mancos Shale). Full-field displacement data extracted from DIC is used in analytical solution to simultaneously determine fracture toughness and crack tip location. Experiments using various fields of view (FOV) around crack tip, ranging from 12x9 mm2 to 48x36 mm2, were conducted; analytical solution was performed by selecting various areas of interest (AOI) and number of terms. Fracture toughness values measured using DIC and load-based calculation are then compared, allowing to choose an optimal FOV, AOI and number of terms for analytical solution for laminated rocks. Despite using Mode I SCB test configuration, mixed mode fractures were observed and quantified using full-field deformations. Effect of different notch orientations to bedding plane on fracture toughness was evaluated for laminated samples. Fracture toughness values are higher when notch is oriented perpendicularly to bedding. DIC is also used for visualization purposes – full-field strain view allows to track strain evolution with respect to bedding, which improves understanding of fracture propagation in anisotropic environments.

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