Optical 3D Deformation and Strain Measurement

The aerospace industry was an early adopter of the 3D Image Correlation technology for full-field deformation and strain studies of their advanced materials and structures. This same technology has been widely used for the analysis of a broad range of materials ranging from manufacturing, automotive quality control, microelectronics and biomechanics applications.

Fig. 1: Preparation for Strain Test of Riveted Area of Aircraft

Because of its accurate and full-field nature, it is the best tool for computer model validation and iteration. The high speed ARAMIS 3D Image Correlation system was chosen by NASA for the Return-to-Flight of the Space Shuttle LS-DYNA model validations [4]. A related system monitors quality at Ford stamping plants, and automatically downloads comparisons to FEM data of real line parts directly into the Ford Quality Control System [14].

Digital Image Correlation (DIC) has greatly benefited from the explosive growth of computer power and digital camera technology. We used to perform full-field optical measurements with laser holography (ESPI), but ARAMIS has replaced most of this technology with its simple method of stereo imaging, which use a pair of video cameras, like our eyes, to measure materials and structures in 3D space, but quantitatively down to the micron world[13]. This system measures any solid materials. Deformation and strain are material independent, so it works well for any solid from ceramics to thin films. Fields-of-view are solely optics dependent, so the technology is capable of performing measurements from 100m's (wind turbines & bridges) [2] to sub-micron volumes (crystalline structures) [5]. Since ARAMIS measures with 10,000 measurement points, it's like having a finite element program for real testing, which compares directly to FEA models. Advances in high-speed cameras have allowed the technology to measure high-speed events from impact, ballistic and blast to split-Hopkinson bar and shock at up to 1M frames per second (fps)[3].

Fig. 2: Vibration Modes on a Tubular Structure

Theory of 3D Digital Image Correlation

The 3D shape of the structure under test is recorded by a stereoscopic pair of high resolution CCD cameras. Typically, the undeformed reference measurement image is compared to the deformed images, and a correlation algorithm measures the relative movement and shape change of a random or regular pattern that had been applied to the surface of the test object [15]. The result is the calculated local displacements and surface strain with a measurement sensitivity of 1/30,000 the field-of-view for displacement (20 microns/meter) and 100 microstrain. Using a tensile load frame as an example, the stereo camera pair on a tripod mounted camera bar (the

ARAMIS sensor) can simply be placed in front of the test sample at the correct working distance, which is relative to the measuring area and lens type.

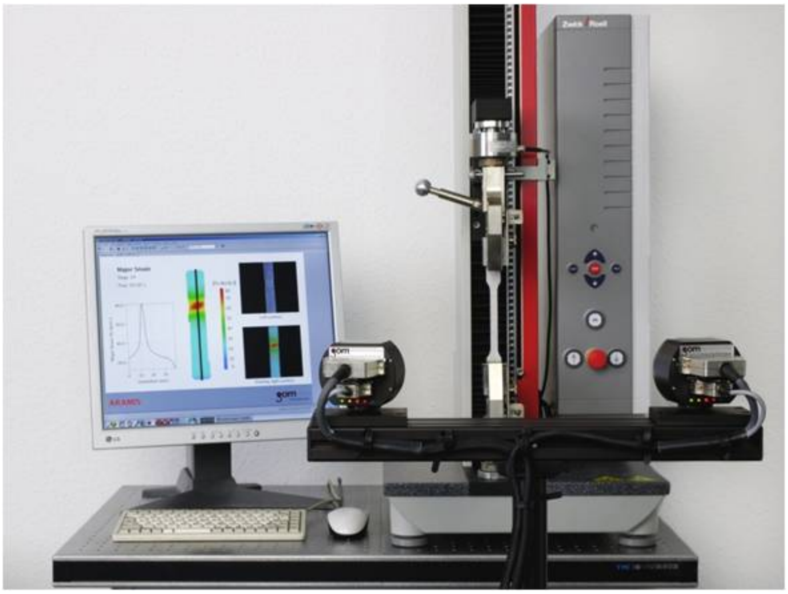


Fig. 3: Typical setup of ARAMIS sensor measuring tensile specimen

Because rigid body motion has no effect on the measurements, this type of setup is perfectly adequate for use with servo-hydraulic machines. A random dot pattern is applied to the surface of the test object, as simply a sputtering on some spray paint. This simple dot pattern deforms along with the object. The deformation of this pattern under different load conditions is then recorded by the CCD cameras and evaluated. This setup is easily performed and can be applied to a multitude of test artifacts large, medium, small, and micro. The equipment operates independently of environmental conditions and as previously stated is not affected by rigid body motion making this setup ideal for measuring strain and deformation in extreme environments from the test lab to the field.

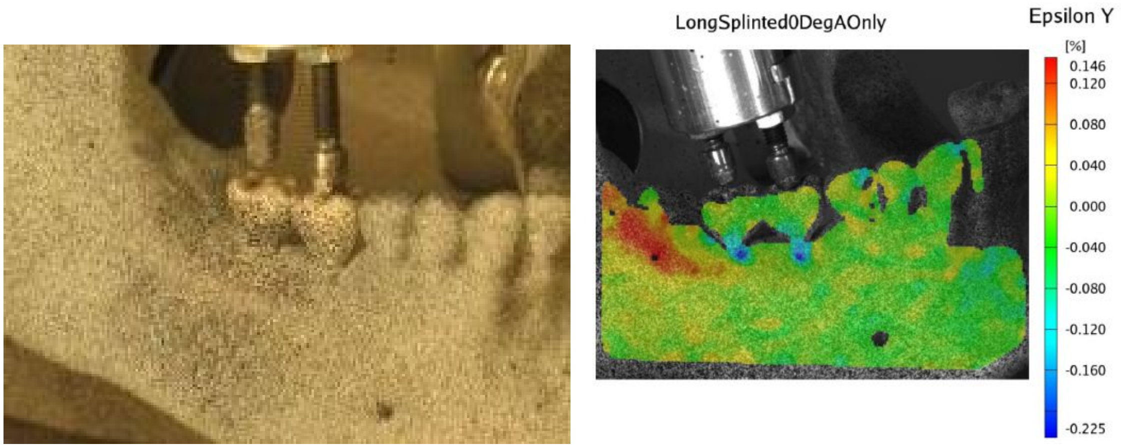


Fig.4 a/b: Patterned Jaw & Implant Teeth and Strain Result c/o OSU

Using a standard 5 megapixel camera, we will discuss the Pixel vs. Facet relationship and how strain is measured. The 5M camera is 2450 by 2048 pixels. The surface coordinates of our sample are measured with small windows or facets, which are typically of 10-30 pixels square. {Fig. 23: A Facet (green square) is a small window (~15 pixels) seeing a target grey-level pattern on the object surface, accurate to 1/1000 pixel. The image may have 10,000 facets across.} Each facet sees specific grey-level pattern which it defines as a unique target, and is then trackable in 3D coordinate space. 10,000 of these facets (or nodes) cover the entire imaging area. The grey level variation within each facet pattern is measured and mapped. Each facet is then a target on the surface of the part, with its own unique characteristics, and specific X, Y, Z coordinates. As long as the facet pattern target remains visible in the image, it can be tracked as it deforms and strains throughout the duration of the test. The center of each facet is a measurement point that can be thought of as an extensometer and strain rosette end point. These facets are tracked in each successive image with sub-pixel accuracy, to one thousandth of a pixel. Then, using photogrammetric principles, the 3D coordinates of the entire surface of the specimen is calculated precisely. Each 3x3 matrix of facets is a strain rosette, allowing the true strain tensor to be measured.

Before the test begins, the calibration process is a critical step for achieving high accuracy measurements. The process uses the dimensions of a known calibration specimen, which is ISO-9001 certified and traceable to NIST. The accuracy of the measurement relies on having the information of the intrinsic and extrinsic parameters of the system. This is easily accomplished by taking images of the calibration artifact under different perspective views. When calibrating to a 55mm field of view, a 3D measuring cube is defined where the distances of all points within this theoretical cube are known in the X, Y, and Z dimensional space. After photogrammetric triangulation, the resolution out-of-plane is 1/100 pixel and the in-plane (strain) is 1/300 pixel. Finally, a bundle adjustment algorithm calculates focal length, lens distortion, and light diffraction for each camera and its individual orientation [22].

Once the 3D coordinates of the entire surface are known, throughout the test, just like a FEM, all of the 3D deformations and strains can be calculated, including deformation and strain rates [21].

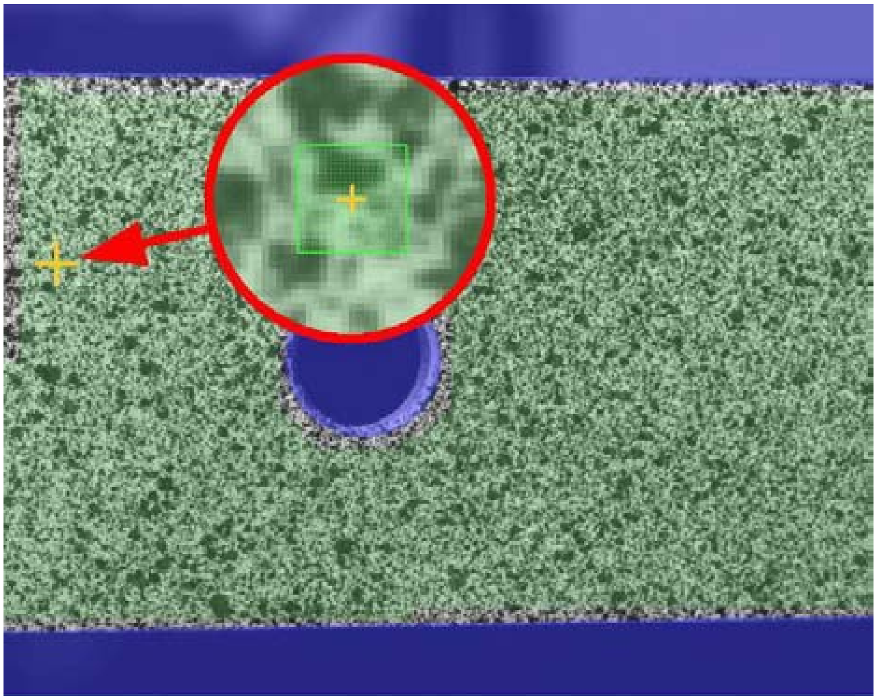


Fig. 5: 3D Deformations & Surface Strains are calculated just like FEA

The software provides complete computer modeling tools to analyze and report all of the measurements, just like standard modeling programs, and will also directly compare the experimental results with the model, for model iteration and validation.

Validating 3D image correlation data with strain gauges is done by most users for their own learning and for personal acceptance of the technology. The most extensive study on the comparison between 3D image correlation and strain gauges has been done by Lawrence Livermore National Labs [7]. LLNL has documented that the image correlation strain data correlates well to strain gauge data. Strain gauges have their own limitations that are generally overlooked or accepted[29]. Image correlation however offers measurement abilities and features not available with strain gauges. The resolution of strain gauges is on the order of 20-30 microstrain, while image correlation is on the order of 100 microstrain. However, strain gauges provide the average strain over a small area and the working range of strain rosettes, typically cannot exceed 1.5-2.0 % strain. Image correlation can capture very local strains, and by adjusting the virtual gauge length in the software, strain data can be as local or global, as required for a test. Image correlation can also be used on strains up to hundreds of percent. Full field imaging of strain displacement gradients make the technique an essential tool for measuring strain on any surface.

Materials Testing and Computer Model Validation

A standard application of the ARAMIS technology is for materials testing, using standard load frames (tensile, compression & fatigue) [27,26]. Variations include bulge testing for automated forming limit curve measurement [10], to deep drawing materials studies [25], providing measurement abilities not possible with traditional methods. The method becomes critical in anisotropic materials such as composites to biomaterials, where the single point or average measurements mean very little.

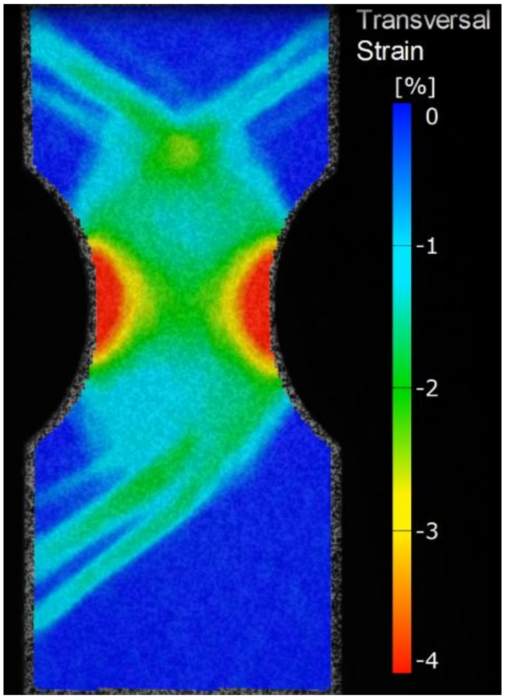


Fig. 6: Transverse Strain of Composite - complex Luede Bands

Even on simple rolled Al sheet for the auto industry, the anisotropy defines the material properties (Hall-Peche Effect) as well as transverse rolling weaknesses. The industry is only just beginning to fully understand it. The ARAMIS system connects to the testing machine, reading the load and displacement of the crosshead (8 A/D channels) and its data collection is fully programmable (re: image every 100 lbs). Most 3D DIC tests consist of 30 - 300 image pairs or stages (1000s are common too). Each stage consists of two camera images (right/left) and a calibration file that relates them. Each stage result is the 3D coordinates of 10,000+ facet points (targets, nodes) across the surface of the specimen. Each facet point is like one end of a clip gauge, a strain rosette node, and an LVDT. ARAMIS then tracks these points throughout the test, so their complex 3D deformations and strains are measured, calculating the true strain tensor for every point.

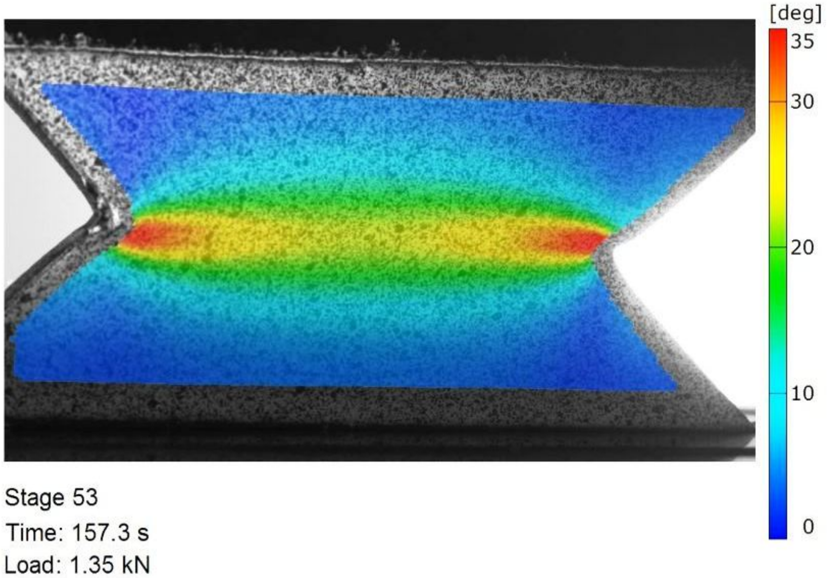


Fig. 7: Shear loading

Shear strain is many times quite difficult to measure locally or more importantly over larger areas; for DIC it is quite easy to measure true shear strains across entire structures, from tissues to bridges. Composites are ideal applications; Jack Coate (Air Force Research Lab) said, "How could we measure it any other way?"

This becomes particularly important for model validation [12]. For example, the result image shows the comparison of a complex X-joint loading.

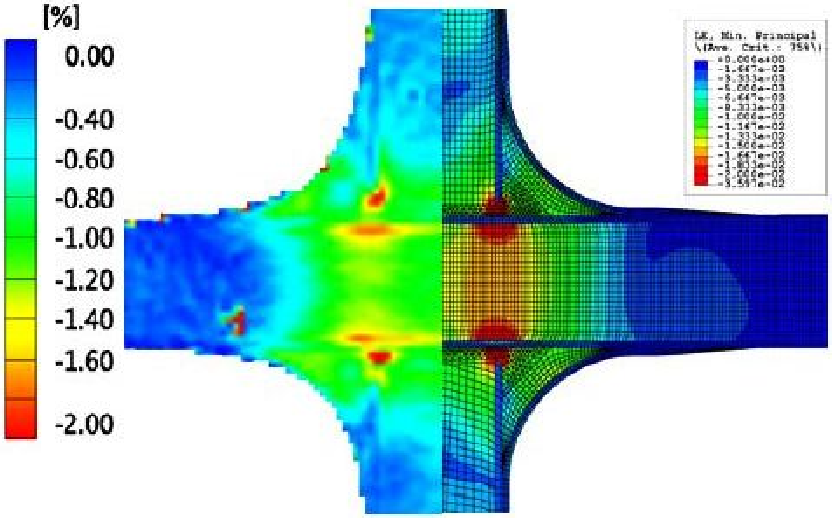


Fig. 8: FEA comparison of real complex X-joint loading with ARAMIS

The full-field ARAMIS data shows the real local deformation and strain variation, as well as the locations of maxima and minima. This is critical information for model iteration, typically of boundary conditions, and for the FEA validation. A model iterated to match the real sample becomes a much more accurate analysis, allowing advanced simulations to model the real material responses. This is a critical step towards the next advances in design and manufacturing.

High Temperature Measurements

Since 3D Image Correlation is a fully optical method, non-contact operation in hazardous environments is a unique ability. Accurate high-temperature measurements are readily achieved through an oven window or in open air. As long as the cameras are not directly affected by the hazardous environment, they maintain their calibration and are accurate; light is basically unaffected by the environment. Deformation and strain measurement up to 1400ºC is typical. This equipment is being used daily for high-precision measurements of thermal expansion of low CTE ceramics to 1000ºC. Incredibly, precision materials measurements within the blast of a jet engine thrust are performed from a 50ft boom[28].

Fig. 9: ARAMIS Thermography from a boom overlooking the B2 Aft Deck c/o AFRL

Induction heating of an advanced bi-metallic component was achieved using highpass infrared filters called heat filters and other techniques. The result below shows the shape of the part and the strains from the tensile load at temperature.

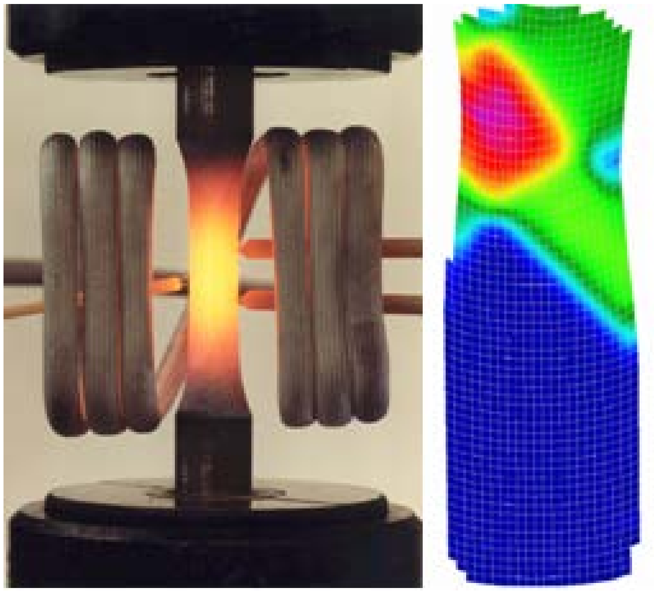


Fig. 10: Bimetallic specimen at 1000°C.

The DIC method is also regularly used through oven windows. Under these conditions, the oven window becomes part of the optical system and needs to be part of the system during calibration. Materials measurements of deformation and strain in the blast of a jet engine thrust can only be described as impossible measurements in a hazardous environment, but are easily achieved with ARAMIS. The key requirement to operation in a hazardous environments in that the surface coating on the material must be able to survive the hazardous environment. Fortunately, the specifications of a measurement coating is quite broad and really only needs to have some amount of contrast and good detail. Blades in a jet engine have been running for months and the creep strain will be measured when they are removed for their next maintenance. ARAMIS Thermography combines DIC with a thermal camera, mapping both data sets together, allowing the temperature and the strain to be overlaid. In addition, the strains can be corrected for thermal expansion, providing the true mechanical strains, even of complex systems, such as automotive engines.

Microelectronics

Thermal expansion of circuit boards and components are critical to microelectronic design and manufacturing. As an example, package warpage has become a serious problem in solder joint reliability, especially with ball grid array packages because of area array solder ball location. Researchers have tried to measure warpage level directly for better understanding of packages [9]. Some efforts have been made to evaluate package warpage in terms of various design factors by using simulation technology. However, simulation requires verification process including adjustment for assumptions made during analysis. Three-dimensional analysis, measuring total deformation of complex objects and their shape, rather than relative deformation, is necessary. Traditional methods such as shadow moiré cannot measure the full response of the package materials [24].

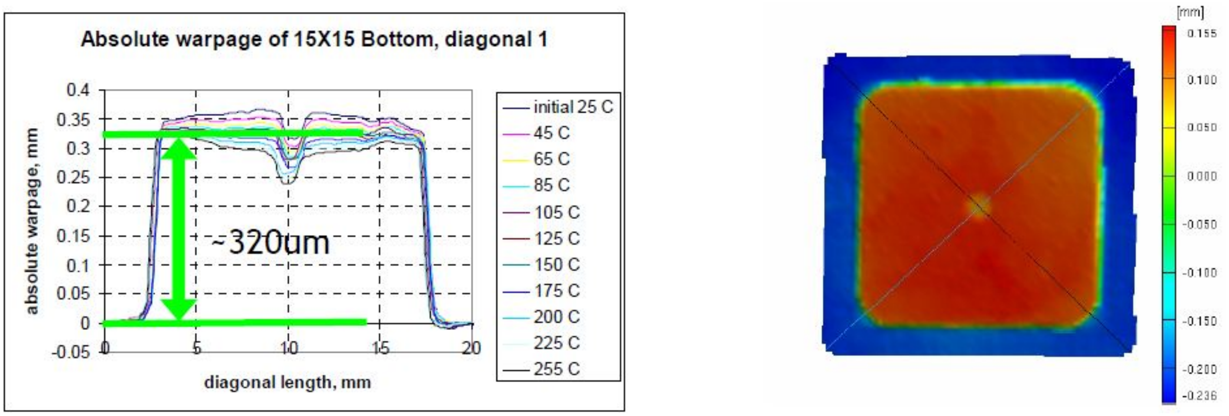


Fig. 11: BGA warpage measurement c/o U.MD

It is well known that ball grid array package warpage due to mismatch of CTEs among materials in structure and geometric asymmetry affects the reliability of solder joints in BGA devices. This warpage, measured with DIC, can be implemented for simulation verification, prediction of design or manufacturing defect, or the introduction of an enhanced package, as the warpage characteristic can be identified as an important design parameter for optimum mechanical/thermal solution for BGA packages.

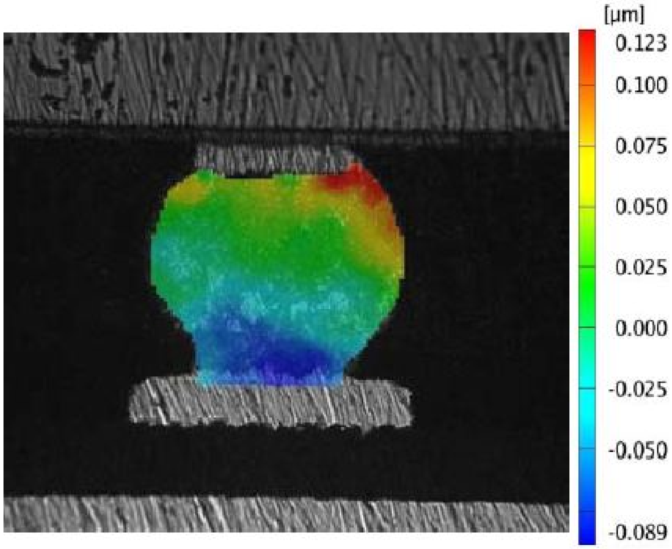


Fig. 12: Solder ball displacements and strains measured c/o Binghamton Univ.

Additionally, measuring alignment of parts (bore sight alignment), such as laser packages to complex opto-mechanical components is easily performed with ARAMIS, because the 3D coordinates of all components in the field-of-view are known simultaneously[6].

Biomechanics

All biomaterials are non-homogeneous and of a complex shape. Non-contact, full-field measurements of local deformation and strain is crucial for the understanding of biomaterials and their interactions.

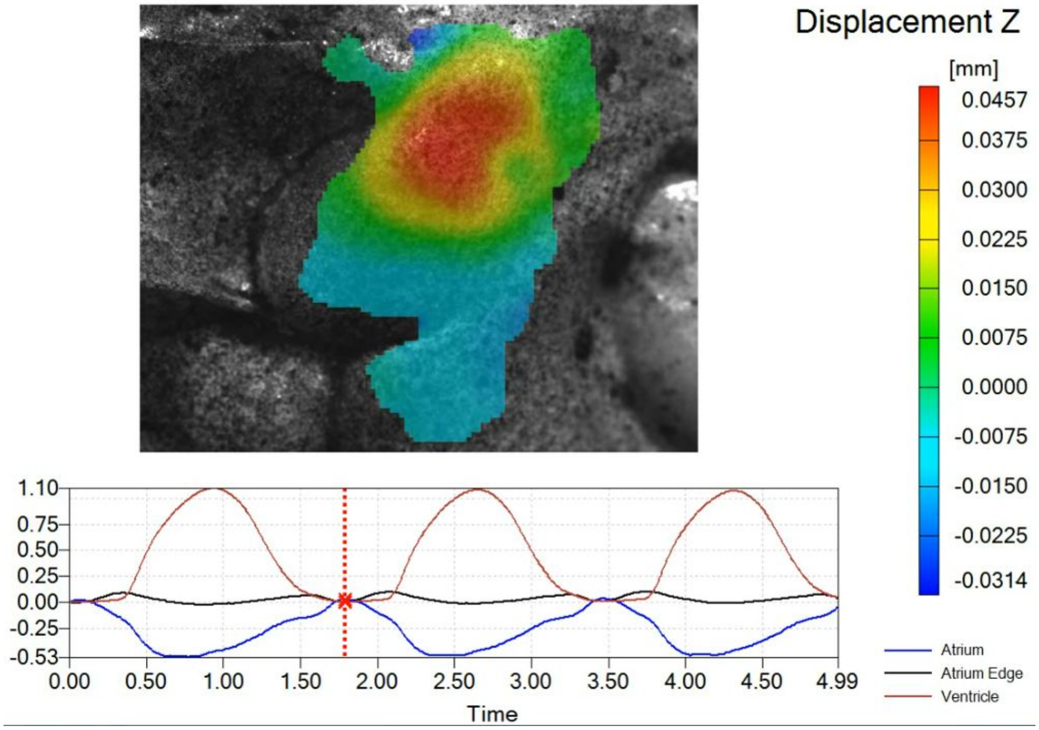


Fig. 13:Blood pumping into Atrium in a Frog Heart c/o Union College

From shaving to running shoes, from tissues to functioning organs, 3D image correlation provides a holistic measure of bio systems. ARAMIS has been used to study the breakdown of the anisotropic behavior of blood vessel walls creating an aneurism, the load response to tendons and ligaments for autocrash model iteration[8]. Studies of fragile tissues of the brain and meninges have lead to deeper understanding of their response under load. Even bone response is highly complex in its behavior due to its composite fibrous construction, from human femurs to mouse tibias[23].

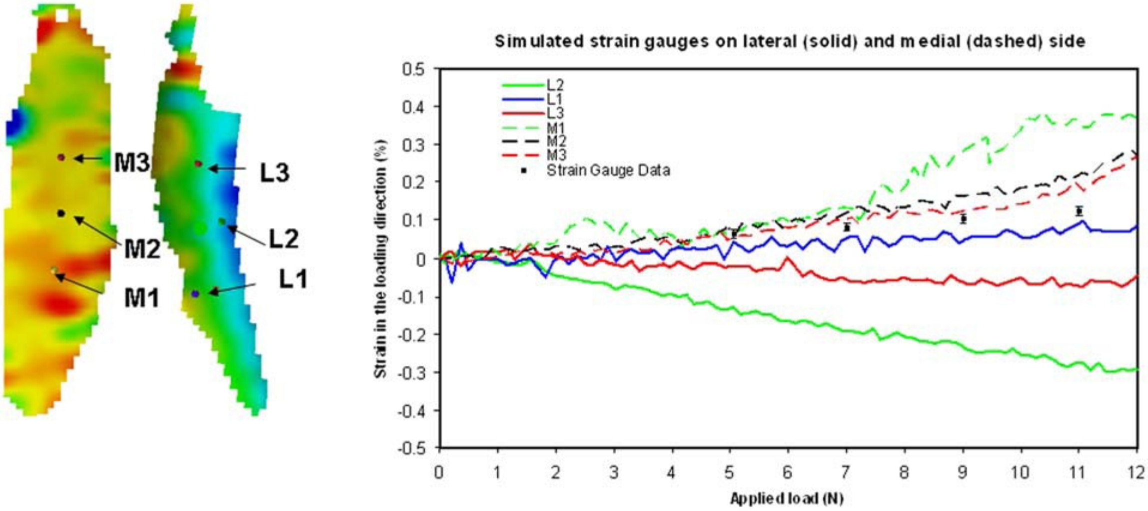
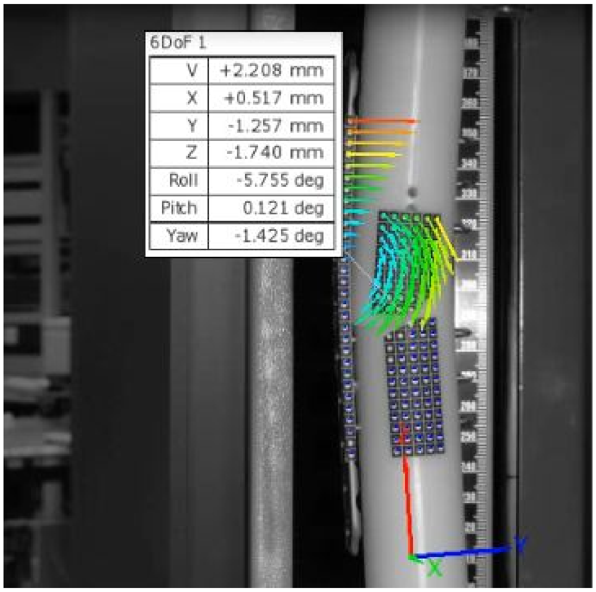


Fig. 14: Mouse Tibia strain measurement c/o Imperial College

The measurement of strain in tissues to bones allows ARAMIS to be a broadly applicable tool for the understanding of the complex motions and interactions of bio systems and biomechanics. Studies of implantable devices have included strains on operating bio pumps (see Figure 11, page 1) and effects of catheter implanted devices on the surrounding tissues.


6DoF 1

V	+2.208 mm
X	+0.517 mm
Y	-1.257 mm
Z	-1.740 mm
Roll	-5.755 deg
Pitch	0.121 deg
Yaw	-1.425 deg

Fig. 15: Deformation Vectors of Bone Screws to applied load.}

In one study, we used lemon Jello to accurately simulate the brain, while we implanted a brain stem pain disturbing effector. ARAMIS was used to measure the effect through the clear lemon Jello of the effectors motions from applied exterior motions to the cables.

The study of vibrational and impact loading on bio systems has broad applications from work place repetitive injuries to shock trauma. DuPont and Aberdeen Proving Grounds have used ARAMIS to study the effects of ballistic impacts on defensive materials and the humans inside, while Wayne State University and UVA study auto crash trauma to brain and skeletal damage respectively.

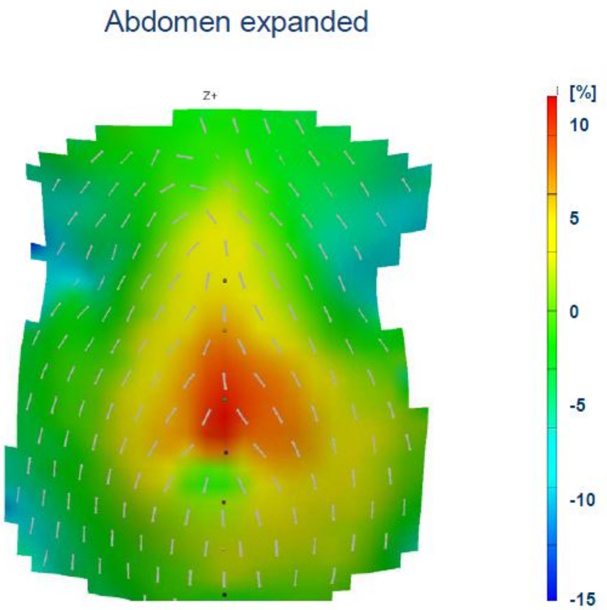


Fig. 16: Abdomen Distension Study

Structural Testing, Modal Analysis and NVH

Four ARAMIS systems were just used on the critical Boeing 787 static test to 150% operational load, the largest test of its kind ever performed, with over 9,000 wired strain gauges.

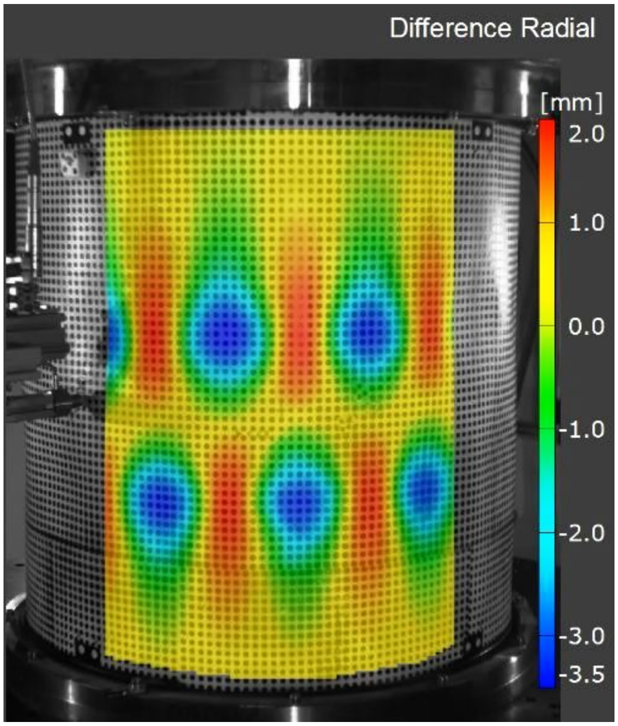


Fig. 17: Modal Analysis of a Motor Segment}

ARAMIS provided an additional 50,000 optical strain gauges covering four critical areas of the wing root. These critical measurement areas were around the area that had unexpectedly failed the year before, jeopardizing the entire B787 program. ARAMIS is becoming a critical tool for the aviation industry.

Bridges have different issues such as large scale deformation over time (years) and crack propagation. ARAMIS was used last year to study the shear strains in a concrete bridge that we took to failure over six hours. The deformation and cracks were monitored in real-time and with little set-up time (1 hour), versus the ~50 wired gauges that took two weeks to set up using a conventional system.

Wind energy turbines are the largest systems that we currently study, with fields-of-view of up to 100m, monitoring windmill blades in manufacturing and during operation.[2]

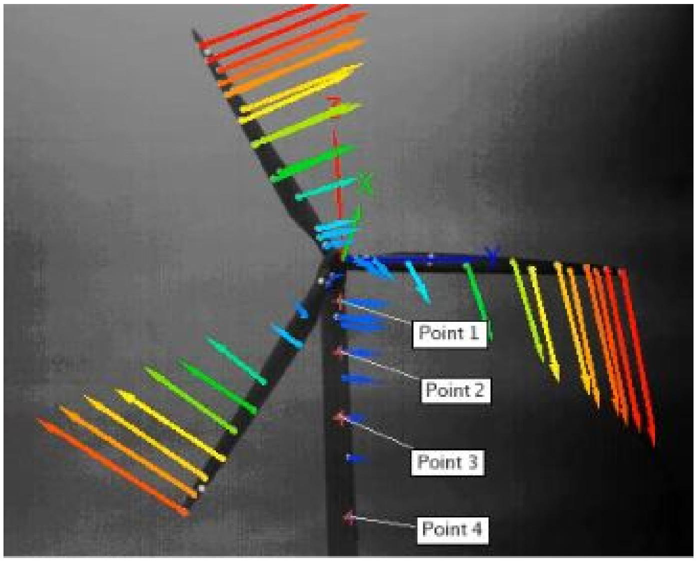


Fig. 18: Wind Turbine deformation during Emergency Stop

The study of the loading and vibrational response is used to validate the FEA. Modal analysis and model validation are powerful applications of DIC [19]. The use of synchronized flash illumination, extends the applicability of 3D image correlation to high-speed rotating components, providing unparalleled synchronous measurement capability. The full-field vibrational or modal response of the system can be easily measured of all points simultaneously. Scanning Laser Vibrometers make huge assumptions about the phase relationship of one point to the next, many times displaying incorrect structural modal responses. Our DIC/photogrammetry software automatically detects the excitation signal and phase steps the measurement to capture all of the modal waveform.

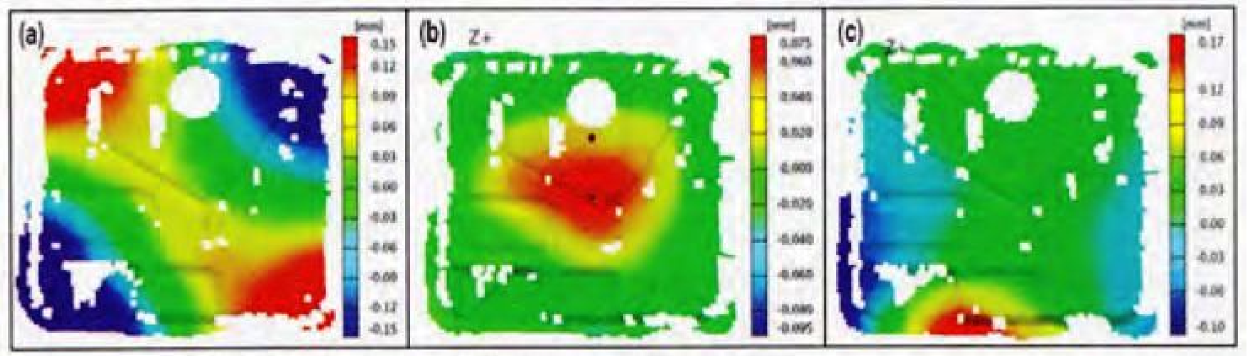


Fig. 19: Vibration Modes used to Validate Model

Various illumination types provide different speed response; faster illumination pulse times allow for measurement of higher frequencies or rotational speed. Microsecond Illumination with Xenon flash and spark gap sources allow testing on dynamometers at hundreds of rpm, while Nanosecond Illumination with pulsed laser illumination facilitates strain measurements during spin pit testing on very high speed rotating components. An 18” diameter flywheel at 35,000 rpm is well within the dynamic capability of the system.

High Speed Testing

The 3D image correlation technique is applicable to any recorded images independent of frame rate. High-speed cameras that have the ability to capture images at 500 to 1,000,000 fps are well suited for high strain rate applications such as drop tower, crash, impact, and ballistics tests. Ultra-high-speed tests (300KHz), such as Split-Hopkinson bar and shock studies using DIC as a non-contact, full-field method, are providing a new tool for physics[3]. The strain sensitivity of static tests (100 microstrain) is the same for high speed tests. There are, however, a different set of considerations for high speed tests. The amount of light necessary is much higher due to the significantly reduced exposure times, and the focus must be perfect to minimize blurring. In order to achieve these very high frame rates, high speed cameras reduce the number of pixels that they use, because their bandwidth is limited to so many Gbits/sec. The tradeoff for any high-speed test is the temporal resolution (frame rate, samples/sec) verses spatial resolution (pixels, no. of pixels covering the field-of-view). The faster that you want to go to capture a temporal event, such as a shockwave, the less pixels can use, reducing your spatial resolution or field-of-view.

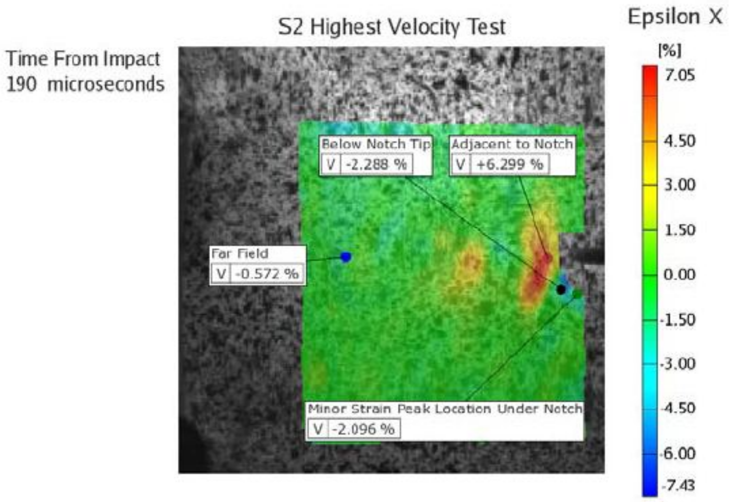


Fig. 20: Fracture at 1M Frames per Second

For the Return-to-Flight of the Space Shuttle, two of the ten required steps defined by the Columbia accident investigation board were to develop current computer models for the foam impact into the carbon-carbon leading edge, etc. (previous models were from 1975) and to validate the new models with experimental tests (previous models were not validated). NASA validated and chose ARAMIS to make full-field measurements for the LS-DYNA model validations[4]. These ballistic studies were performed at about 30,000 frames per second. Even, individual carbon-carbon fibers were measured fracturing during impact, which really helped validate the models down to the macro scale.

Summary

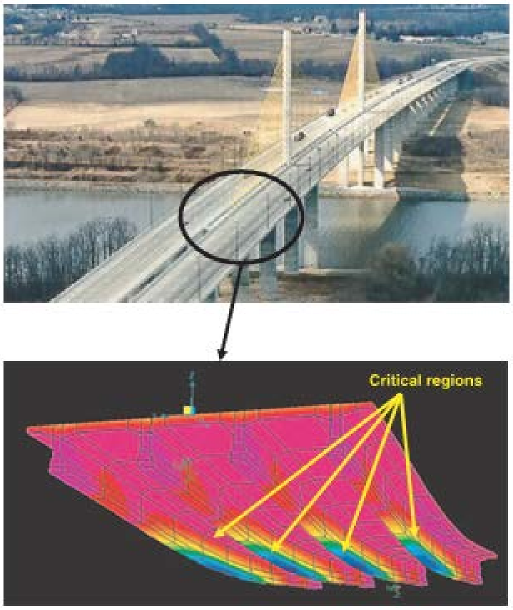
3D Optical metrology with Digital Image Correlation photogrammetry is the next generation of engineering tools, replacing the majority of wired sensors with precision optical measurements. Formerly, you had to "guess" where to mount, wire and calibrate your strain gauges, clip gauges, LVDTs, etc. Since you are imaging the entire area, your sensors can be placed after the loading, when you know where you want a measurement, even a year later. DIC measures strain, in-plane displacement and out-of-plane displacement, at all points continuously. It can measure any material, from ceramics to thin films, and uniquely complex combinations of materials found in real structures. It can also measure under most stressing mechanisms, from mechanical, thermal, and vibration loading, in a fully non-contact and simple way. The data is complete and precise, and is ideal for the iteration and validation of computer models, making these models more accurate at modeling the real structures. This will take modeling and simulations for advanced designs to the next level of refinement, allowing industry to advance to a new level of capability.

Manufacturing optical measurement systems for digitizing, forming analysis and materials analysis are a becoming a part of advanced process chains for the development of products and production processes.[16] Already today, time, costs and quality are being optimized with the use of optical metrology, thus increasing the competitiveness of our companies. These measuring technologies are used increasingly for automated inspection tasks with their further integration in processes and the availability of ever more powerful data processing systems. This data is now linked and automatically uploaded to the quality control systems for precision lean operations globally.

Fiber Optic Strain Gauges

Optical-fiber sensors are emerging as a excellent non-destructive means for evaluating the condition of aerospace composites and concrete structures. In contrast to existing non-destructive evaluation techniques, optical fibers are able to detect minute variations in structural conditions through remote measurements. Structures fully integrated with optical fibers are able to be monitored for the initiation and progress of various mechanical or environmentally-induced degradations in structural elements. Fiber-optic sensors have been extensively employed as real-time damage detection tools in advanced aircraft and space vehicles, embedded in their composite structures. External perturbations such as strain, pressure and temperature variations induce changes in the phase, intensity or wavelength of light waves propagating through the optical fibers. The change in one or more of these properties of the light can then be related to the parameter being measured.

The smart material concept takes advantage of the geometric adaptability of optical fibers, which are embedded within the structural material for the purpose real-time monitoring and damage assessment. Besides ruggedness, flexibility and extremely small diameter, optical fibers are immune to electric and electromagnetic interference. Fiber-optic sensors are have the inherent ability to serve as both the sensing element and the signal transmission medium, allowing the electronic instrumentation to be located remotely from the measurement site. The advantages of using embedded fibers in composite structures include the dimensional and material compatibility, and the fibers do not degrade during curing, they do not corrode, and the bond strongly into the matrix. Incorporation of the fibers during the processing stage also offers the opportunity to monitor the condition of structural elements during fabrication and installation.



The use of optical fiber sensor technology for the condition monitoring of civil structures in order to detect cracks, improve durability and safety. The proper application of fiber-optic sensors to large civil structures requires understanding of sensor measurement methods and multiplexing strategies. Fundamental issues such as sensor type, embedment techniques and specific sensing locations are among the practical concerns of the Civil Engineer. Cracking is among the most important parameters that directly influence structural design and durability of concrete constructions. Locating the sensors in the locations of the critical stress regions is critical.

The three primary transduction mechanisms through which optical fibers sense the physical or ambient perturbations are based on intensity, wavelength, and interference of the lightwave. Most of the current sensor designs are wavelength or frequency based such as fiber Bragg gratings (FBG) and interferometric sensors based on Fabry Perot, white light, etc. However, other sensor designs such as those based on intensity modulations of lightwaves as well as Brillouin scattering have been developed and effectively employed in civil engineering applications.

From the engineer’s point of view a very effective way to utilize an optical fiber is to integrate a single sensor throughout the structure for detection of all anomalies and cracks. At the sensor level, single channel distributed sensing, geometric adaptability, immunity to electrical and magnetic interference, elimination of lead lines, optical transfer of information, high resolution, and high signal to noise ratio are amongst the many attributes of optical fibers. In practice, it is necessary to design the sensor considering the current technological limitations and the logistics involved for the particular structural application. Some of the issues to be considered are:

- Sensor configuration to detect parameters of relevance, i.e., cracks, forces, corrosion
- Packaging the sensor for conformity within a diverse set of construction materials
- Installation in a harsh construction environment, durability, and survivability
- Calibration and referencing for long-term sensing
- Long-term stability and reliability
- Multiplexing and distributed sensing
- Dynamic range, resolution, and sensitivity
- Data acquisition, analysis, and management (i.e. software-supported)
- Cabling, leads in and out of the structure
- Calibration and referencing for permanently integrated sensors

Optical fiber sensors when properly utilized provide superior structural health monitoring capabilities in civil structures. The primary advantage of optical fiber sensors in structural health monitoring is the geometric conformity and capability for sensing of a variety of perturbations. Properly configured sensors will be able to sense the structural effect of importance without affecting the structural behavior.

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