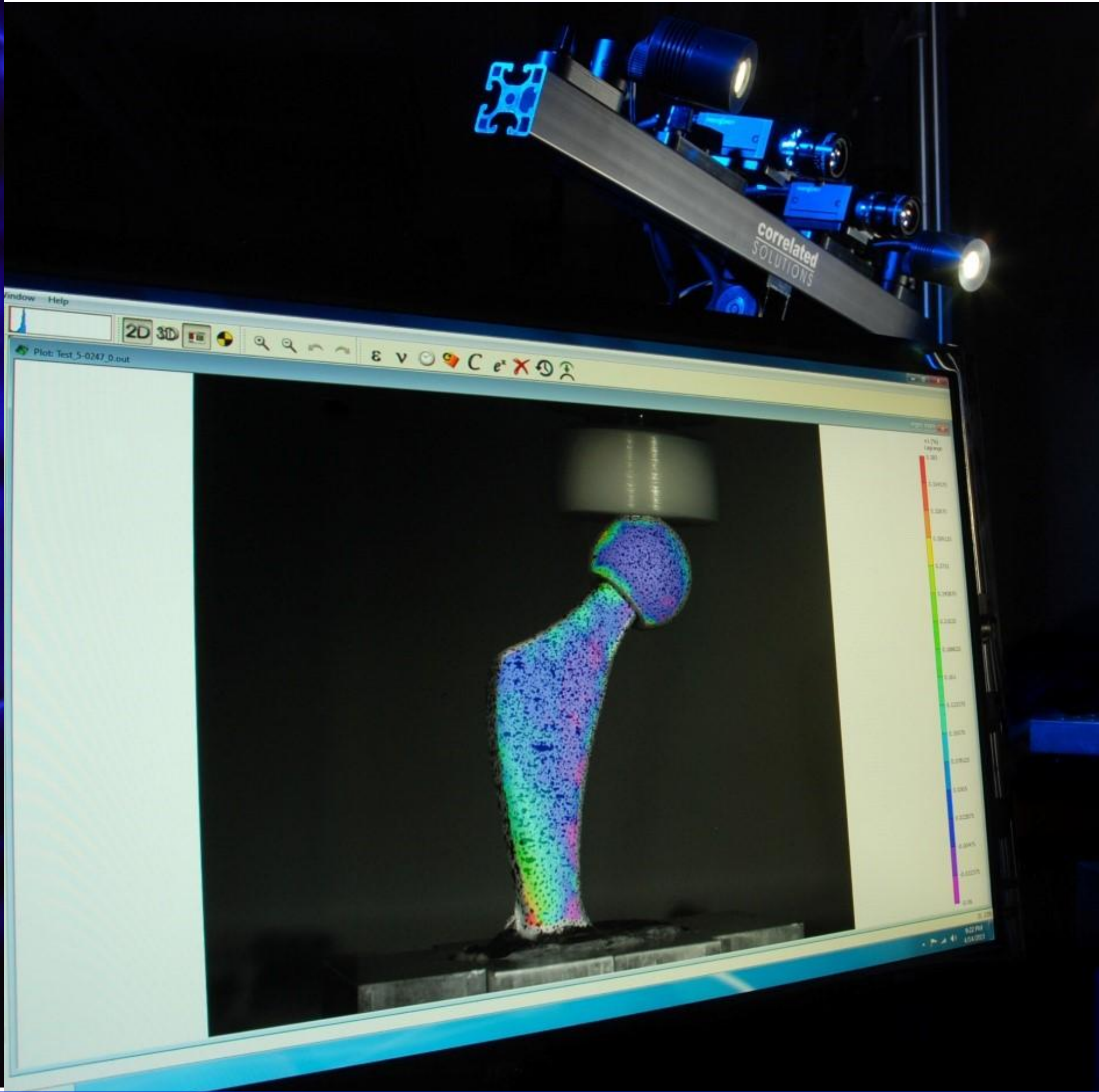

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DIGITAL IMAGE CORRELATION

ITS BENEFITS TO INDUSTRY

LUCIDEON
providing material solutions

INTRODUCTION

Digital Image Correlation (DIC) is a non-contact, non-interferometric measurement technique that uses high-resolution machine-vision digital cameras to accurately measure surface deformation in two or three dimensions. This measurement is presented graphically in several ways such as a 2D strain map overlaying the test specimen, or a 3D displacement map showing the specimen surface and how it moves throughout the test.

Early development of this technology began in the mid-1980s in the mechanical engineering department of the University of South Carolina. Since then, it has gone on to revolutionise mechanical testing on both the macro and micro scale.

The applications of DIC are vast, from eyeball pressure testing to earthquake analysis; this adaptable and highly capable system will transform design, validation, and testing methods for anything from dental implants to wind turbines.

THE PRINCIPLE OF DIC

The DIC system is based on the ability of high-resolution cameras to track a black and white speckle pattern on the surface of an object as the object deforms. The calibrated cameras take an initial image before any deformation occurs and uses this image as the reference, or start position, for a variety of calculations. The cameras can then record images at a defined rate throughout a test; these are then processed by the computer analysis software.

In the post-analyses the software divides the reference image up into subsets. Each subset has a pre-defined pixel size which can be changed depending on the speckle size or type of analysis required. A unique greyscale number is given to each subset which is assumed to remain constant throughout the deformed images. By using a correlation equation, the DIC software can track these subsets across the various deformed images by identifying the unique grey scale level for each subset.

MAPPING

To calculate the correlation coefficient, the relative position of the deformed image to the reference image needs to be calculated. The software does this by forming a linear mapping function, which assumes the deformation on the surface of the object follows the translation.

CORRELATION PRINCIPLE

Correlation equations are used to match the original image subset to the subset in the deformed image. There are numerous correlation equations which are used depending on the specific system software, all of which will yield the same results. The correlation works by matching the original subset to the deformed subset with the highest accuracy possible.
To obtain the highest possible level of correlation between the reference subset and the deformed subset the sum of the square difference between greyscale levels is minimised. By using the following correlation equation, the DIC can match the original subset to the deformed subset with an accuracy of greater than 0.01 pixels.
Correlation Co-efficient C

$$C\left(u_i, \frac{du_i}{dx_j}\right) = \iint_m [A(x) - B(x')]^2$$

$$i, j = 1,2$$

Where A(x) is the intensity distribution from the reference image and B(x') is the intensity distribution from the deformed image at point p

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INTERPOLATION

To achieve accurate correlations between subsets the content of the subsets needs to be examined in detail. The DIC software works by converting the light intensity of each pixel into a digital grey scale number ranging from 0 to 255. This discrete data does not truly represent the actual intensity distribution being recorded by the cameras, but rather provides a digital approximation. To achieve a more continuous intensity distribution a bilinear interpolation technique is used.
Using this bilinear interpolation method, the computer system can analyse a more accurate representation of the greyscale level that is present on the object's surface rather than a digital map of what the camera's sensors are picking up. This, along with the correlation equations, provides an extremely accurate approximation of the surface deformation occurring.

There are various other parameters which affect the measurement accuracy of the DIC system. These parameters can vary between tests and need to be considered individually before each test. To achieve reliable calculations, a speckle size, speckle density, and subset size need to be chosen to optimise the software's ability to calculate the various equations explained above.

AUGMENTING TRADITIONAL TESTING METHODS

DIC can be used to not only augment mechanical testing but transform it. Traditionally, to examine strain, strain gauges are placed on the surface of the specimen at points of interest. However, the deformation of heterogeneous material, such as concrete with large aggregate sizes, is complex and the correct placement of strain gauges can be hard to predict. As well as this, for a large specimen, the number of strain gauges required can grow very quickly. With DIC every point on the specimen can be analysed quickly and easily. This can be of particular use in much smaller scale samples with complex topography and tribology where the effective application of strain gauges may prove difficult. Retrospective analysis can also be carried out, allowing the user to add virtual extensometers, line inspections and a host of other inspection tools.

The ability to forego strain gauges and adhesive-dependant measuring equipment offers a distinct advantage to the DIC user. The surface is left undisturbed and in full view. The slow-motion video capture software allows the user to see the strain, crack propagation, and failure modes of the specimen at any point in time.

The convenient size of the system allows the equipment to be set up in front of any test rig, while a voltage output from the test frame can be connected to the system to add another layer of analysis.

FLEXURAL STRENGTH TEST

A common application for DIC is in conjunction with three-point bend tests as illustrated below. Traditionally the user has only been able to determine the load at which the specimen undergoes a specific level of deflection. DIC gives the user the ability to perform an in-depth analysis, examining the failure modes of the specimen, where the maximum strain was located and the force it took for cracks to begin to form.

The high-resolution cameras coupled with the advanced displacement calculating software offer a level of crack detection that is impossible to perform with the naked eye.

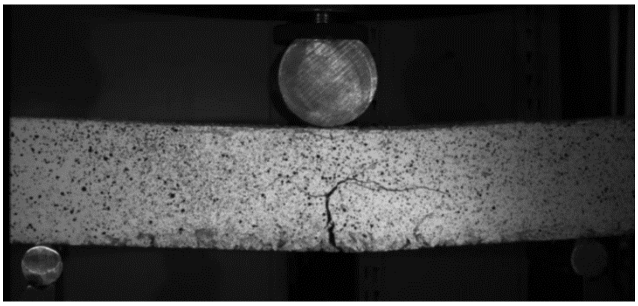

Figure 1.- A specimen under standard load test

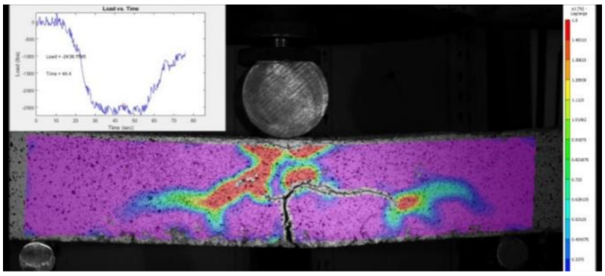

Figure 2.- A specimen under load with DIC

Figures 1 and 2 show the same three-point bend test with and without DIC analysis. In the first image the cracks appear to only have begun to propagate, however the DIC analysis shows that hairline fractures have already occurred extending across fifty percent of the specimen.

CHARPY TESTING

Perhaps the most common material test, the Charpy test (or the V notch test), has been in existence for over a century, with little change or improvement.

Traditionally designed to determine a material's notch toughness, the test relies on calculating the energy absorbed by the specimen when struck by a pendulum. As a result of widespread use there is a compelling argument for as much data to be extracted from the test as possible.

High speed DIC can be utilised for this purpose. The strain at the notch tip can be quantified and graphically plotted against time, allowing the user to determine the existence of flaws in the material that result in rapid propagation of cracks.

TENSILE TESTING

Like the three-point bend test, tensile testing has traditionally been used to evaluate a limited number of variables, in this case, the Young's modulus of the material, the maximum elongation and the reduction in area. However, when examining heterogeneous materials under tension, DIC can give a whole new layer of analysis.

The boundaries between materials in a specimen are often the weakest points. As the specimen is loaded DIC can be used to examine the strain distribution across the specimen. This information can be used to determine the likely effect the composition of the specimen is having on the material's ultimate tensile strength. In addition to this, the virtual extensometers available in the analysis can quickly calculate the elongation between any two points.

Figure 3 shows an example of DIC being used to determine the maximum strain developed in a material under test, as well as the maximum elongation using a virtual extensometer.

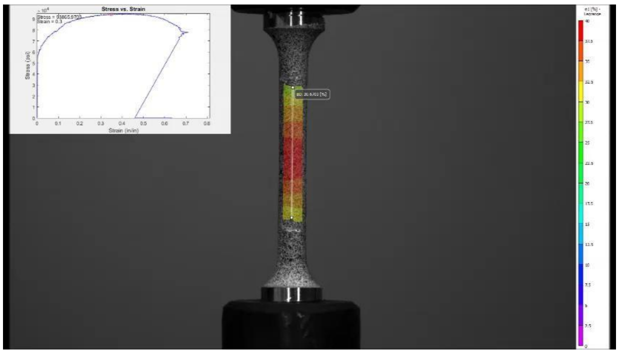

Figure 3.- Tensile test with DIC

COMPRESSION TESTING

As the DIC system uses displacement as the basis for its calculation, it is of great benefit to compression testing. Additional cameras can be added to the system to allow a full field of view of the specimen. This allows out-of-plane displacement measurement at almost 360 degrees.

A problem often encountered during compression testing is how to mitigate against the deviation from true stress and engineering stress caused by the phenomena known as barrelling. Barrelling is the change in shape of the specimen under load resulting in a larger contact surface: thus, energy is absorbed through friction between the specimens and the articulating surface. The use of full field optics, such as DIC allows for accurate calculation of the barrelling profile. This can be used to compute the Coulomb friction coefficient and thus calculate deviation of the true stress from the engineering stress.

A new dimension of compression tests can also be performed on specimens of complex geometry. Previously, finite element modelling was required to accurately predict areas of high strain under various loading conditions. Now, with the DIC system, a finite element model level of detail can be obtained in real loading tests, allowing pre manufacture validation and quality control along the entire manufacturing process.

FATIGUE TESTING

Fatigue testing is an essential part of mechanical testing of any operational component. Often, moving assemblies cannot be tested during operation due to space constraints and difficulties maintaining electrical connections. Inconsistent operating cycles and contact zones between components can cause difficulties in predicting fatigue behaviour and stress concentrations. Full field measurement capabilities of DIC allow comprehensive analysis of entire areas of operation to accurately find regions of high strain and load.

Another benefit in the field of fatigue testing is the ability of the system to measure crack growth in modes I, II, and III.

NOVEL APPLICATIONS OF DIC

Strain calculation is a key factor in mechanical testing of any part. DIC presents testing opportunities in an abundance of applications which may not have been possible prior to the development of DIC technology. The non-contact full-field measurement capabilities allow dynamic temperature testing of independent parts of a wide range of materials under many different testing conditions. This type of analysis has the potential to supply a more in-depth detection and discovery of defect and failure zones - something which may never have been suspected without this method.

FINITE ELEMENT ANALYSIS VALIDATION

FEA (Finite Element Analysis) has become a vital resource when it comes to testing specimens of complex geometry. It is the only way to test a product before committing to manufacturing a prototype, a process which is often costly. However, FEA can present problems when modelling stress and strain of complex geometries, often due to uncertainty surrounding boundary conditions and material properties resulting in error generation.

Validating theoretical computer models is an essential step to designing a quality product with an efficient use of materials. Interest lies in DIC for this purpose. One of the many key advantages of the DIC system is the fact that it measures full-field 3D surface strains over the entire specimen's geometry without any mechanical interaction with the sample. This eliminates the need for strain gauges and saves many man-hours. This is perhaps the most effective and efficient method for validating and refining FEA models.

DETERMINING MECHANICAL PROPERTIES OF SOFT TISSUE IN VIVO

Determining the mechanical properties of human soft tissue is crucial in the fields of biomechanics, rehabilitation engineering and surgical simulation. Post processing data from imaging methods such as magnetic resonance imaging (MRI) can be challenging. These images are often processed into finite element models with defined boundary conditions. Also, material properties may not be accurate, as soft tissue performance varies from person to person. DIC offers a unique solution to this problem. The 3D surface deformation of the soft tissue can be easily calculated using the advanced analysis software and an indentation test. This material property can then be inputted into the FE model, allowing for iterative analysis to accurately determine further tissue properties, such as visco-elasticity and non-isotropy.

Accurate FE models can give both surgeons and rehabilitation engineers a massive advantage when in surgery, or when designing rehabilitation devices such, as prosthetics and assistive devices e.g., wheelchairs.

DIC can also be used as a standalone aid in the development of medical devices. One example of how this technology can be used in industry is in the design of needles. One of the goals in needle design is to minimise the pressure it takes to penetrate the skin, as the higher the force that is needed, the greater the chance of piercing the medial wall of the vein and inducing internal bleeding. Using flesh analogues in conjunction with DIC an analyst can accurately determine the strain experienced by both the needle and the skin when using various needle tip designs.

3D MEASUREMENT CAPABILITIES

While DIC is capable of measuring strain in two or three dimensions, three dimensional measurements can provide enhanced data on further degrees of freedom, allowing translational and rotational analysis in all planes and axes. Using the stereo camera system setup, DIC allows three dimensional in and out of plane measurement within the bounds of the system. This can range from microns to meters and can provide an excellent alternative for certain topographical and tribological measurements of small and delicate samples. Figure 4 shows an analysis of the out of plane motion of a truss system when subjected to a three-point bend test.

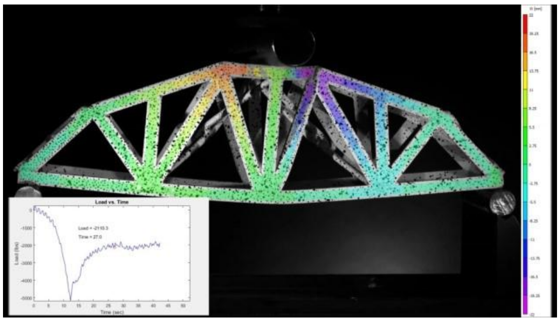

Figure 4.- Out of plane measurement capabilities demonstrated on a Truss System under load

The three-dimensional measurement capabilities offer a unique method of analysing fracture modes I, II, and III - traditionally extremely difficult to measure using strain gauges. The out of plane motion present in fracture mode III means strain gauges do not adhere to the surface, leaving DIC as one of the only valid techniques for analysing this fracture mode.

LARGE SCALE STRUCTURES AND SAMPLES

The versatility of the DIC system is highlighted by the range of specimen sizes capable of being analysed. Using a range of different camera setups, specimen sizes ranging from millimetres to hundreds of meters can be analysed. DIC can therefore be used across all industries from analysing small scale samples, such as medical implants to large scale structures, such as turbine blades and aircraft wings. The ability to transport the system means that testing can be performed on site, thereby reducing the costs involved in transporting large scale specimens. As well as this, testing can be performed periodically, to allow measurements to be taken months, or even years apart.

Long term testing is of particular use in the field of creep testing and structural integrity validation.

CONCLUSION

With increased pressure from regulatory bodies demanding stringent testing throughout the design, validation, and manufacturing phases of product development, Digital Image Correlation offers the most rapid, efficient and complete analysis.

DIC presents a far more comprehensive analysis than previously possible with traditional test methods, meaning problems can be addressed with more effective in-depth solutions.

Optimisation of sample and product performance using DIC is a diverse technique which can be used across many sectors and material ranges as a standalone test or in conjunction with others. Along with a vast computational ability, this diversity allows DIC to be a valuable tool for engineers, scientists, and designers looking to implement solutions and analysis.

ABOUT LUCIDEON

Lucideon is a materials science consultancy, solving its clients' most complex challenges through materials development, process optimisation, and characterisation. Its application of cross-industry insight, materials science expertise, and innovative thinking allows industry to develop and implement disruptive technology platforms, providing cost and/or product performance benefits and enabling real market differentiation. It utilises its many years of experience in development, analysis, and assurance to provide technical consultancy to enable, enhance, and accelerate its clients' R&D activities.

In addition to a multi-disciplinary team of scientists, engineers, and commercial analysts, Lucideon has world-leading testing and characterisation laboratories, a combination of pilot and feasibility plant and equipment, and a management and certification division.

Lucideon has offices and approved laboratories in both North and South Carolina, as well as New York State, and Staffordshire and Cambridge in the UK.

ABOUT THE AUTHORS

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A graduate of University College Dublin, Ross holds a bachelor's degree in engineering having specialised in Mechanical and Medical Engineering. Ross's work at Lucideon focuses on Anatomical Wear Testing and Wear Particle Analysis as well as exploring the applications of Digital Image Correlation.

Evan Guilfoyle – Mechanical and Materials Engineer

Evan is a Mechanical Engineer with a first-class honours bachelor's degree in mechanical and Materials Engineering. Evan has extensive experience in the construction industry as well as mechanical testing and Anatomical Wear Testing.

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Experienced in manufacturing, validation and polymer processing Karl has made significant advances on an FP7 EU funded project involving the development of medical materials for vascular applications. Karl is a graduate of University College Dublin with a bachelor's degree in mechanical engineering.

All details correct at time of initial publication.