

## **Digital Image Correlation Techniques for Non-Destructive Evaluation and Structural Health Monitoring**

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### **Abstract**

Monitoring and analyzing the integrity of structures, infrastructure, and machines is essential for economic, operational, and safety reasons. The assessment of structural integrity and dynamic conditions of those systems are important to ensure safe operation and achieve or even extend the design service life. Recent advancements in camera technology, optical sensors, and image-processing algorithms have made optically-based and non-contact measurement techniques such as photogrammetry and Digital Image Correlation (DIC) appealing methods for Non-Destructive Evaluation (NDE) and Structural Health Monitoring (SHM). Conventional sensors (e.g. accelerometers, strain gages, string potentiometers, LVDTs) provide results only at a discrete number of points. Moreover, these sensors need wiring, can be time-consuming to install, may require additional instrumentations (e.g., power amplifiers, data acquisition), and are difficult to implement on large-sized structures without interfering with their functionality or may require instrumentation having a large number of data channels. On the contrary, optical techniques can provide accurate quantitative information about full-field displacement, strain, geometry, and the dynamics of a structure without contact or interfering with the structure's functionality. This chapter presents a summary review of the efforts made in both academia and industry to leverage the use of DIC systems for NDE and SHM applications in the fields of civil, aerospace, and energy engineering systems. The chapter also summarizes the feasibility of the approaches and presents possible future directions of the measurement approach.

**Keywords:** Digital Image Correlation, Non-Destructive Evaluation, Optical Measurements, Photogrammetry, Structural Health Monitoring.

## **1 – Introduction**

Aerospace, civil, and mechanical engineering structures such as bridges, buildings, pipelines, aircraft, ships, and wind turbines are routinely used despite the reality that many are aging, deteriorating, and exceeding their intended operational design life (e.g., ASCE 2017). Assessing and quantifying the condition of aging structures is essential to verify structural integrity, ensure long-term reliability, and determine when component repair or replacement should be made. A goal in industry is to move away from scheduled based maintenance to condition based monitoring in order to perform assessment of factors that can jeopardize the system's performance. Identifying a strategy to detect damage for engineering systems, structures, and infrastructure is called structural health monitoring (SHM). SHM involves the observation of the targeted system over time to extract damage-sensitive features, determine the current health state, and predict future condition (Farrar and Worden 2007) which is important for damage prognosis and future life prediction. SHM plays a key role in the prevention of catastrophic failures, improving the safety of structures and infrastructure, and reducing the downtime and costs associated with maintenance. Thus, it represents a method for tracking the health of an engineering system by combining damage detection algorithms with structural monitoring devices (e.g., sensors). SHM is often carried in conjunction with another closely related discipline: Non-Destructive Evaluation (NDE) often referred to as Non-Destructive Testing (NDT). Those techniques consist of some evaluation methods to assess the condition of a targeted system without affecting the system's functionality (Shull 2016). Both SHM and NDE techniques allow for early detection and assessment of structural damage to ensure that structures continue to meet life-safety requirements. Because human visual inspection techniques are based on the inspector's opinion, subject to variability, and labor-intensive, this makes automated computer-based monitoring systems very desirable.

Contact-based sensors are commonly used for monitoring a variety of structural systems. One of the most common practices is to record and analyze the data from a network of sensors, either passive or active, embedded or attached onto the monitored structure (Giurgiutiu and Cuc 2005). These methods include both dynamic and static analyses and have significantly improved over time. Contact-based sensors such as strain-gages, accelerometers, linear voltage displacement transducers (LVDTs), inclinometers, and extensometers are commonly used for SHM and NDE applications (Doebbling et al. 1996; Sohn et al. 2003). Fiber optic sensors have proven to be valid alternatives to the

conventional sensors due to their flexibility, Electro Magnetic Interference (EMI) immunity, and scalability (Glisic and Inaudi 2008; Ye et al. 2014). However, these sensors can be difficult to implement, need wiring, are costly, require power, and once attached are generally not portable for interrogation on multiple engineering systems. For resolving these problems, several researchers proposed using Wireless Sensor Networks (Lynch 2007; Sabato et al. 2017a). Nevertheless, even these sensors are typically not durable enough to be attached or embedded in the structure and perform measurements throughout a structures lifespan which may be years or decades after its construction (when failures are more likely to occur). Furthermore, most of these sensors can only provide information at a few discrete points (Calebi 2002).

Recent technological developments have provided new NDE techniques for the assessment of different typologies of engineering systems. Radiography (Udod et al. 2016), radioactive computerized tomography (Hanke et al. 2008), radar (Pieraccini 2013), ultrasonic arrays and acoustic imaging systems (Drinkwater and Wilcox 2006), acoustic emission (Gholizadeh et al. 2015), and infrared thermography (Usamentiaga et al. 2014) have all been implemented for NDE and SHM and each possesses their advantages and challenges. The readers are referred to the studies of Gholizadeh 2016 (composite materials), Rehman et al. 2016, Seo et al. 2015 (bridges), Drewry and Georgiou 2007, Tchakoua et al. 2014, Zhou et al. 2014 (wind turbines), Rizzo 2014 (railroads) for further information, depending on the specific SHM and NDE applications.

New advances in camera technology, optical sensors, and image-processing algorithms allowed the development of a new generation of non-contact measuring methods. Optical-based techniques such as three-dimensional digital image correlation (3D-DIC), three-dimensional point tracking (3DPT) have become valuable tools for performing non-contact measurements and extracting structural deformations, full-field displacement and strain, geometry profiles, and modal parameters in aerospace, civil, and mechanical engineering systems. In this chapter, a review of the efforts made both in academia and industry to leverage the use of DIC systems for performing SHM and NDE analyses are summarized.

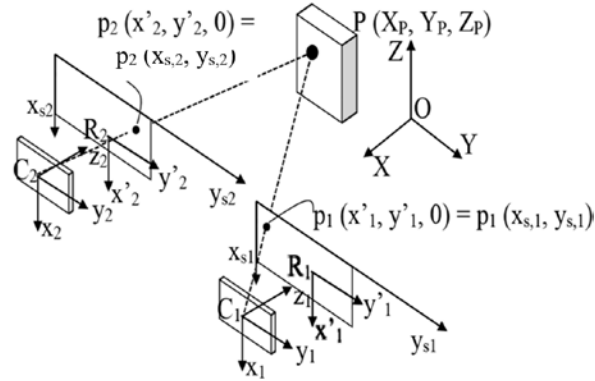
This chapter is organized as follows: Section 2 (Basics of Digital Image Correlation) presents a description of the theoretical foundation of optically-based and computer-vision based technologies. In Section 3 (Non-Destructive Evaluation and Structural Health Monitoring using Digital Image Correlation) a detailed report of the

state-of-the-art of computer-vision based systems employed for SHM and NDE applications is discussed. Finally, future work is briefly outlined in Section 4 (Future Directions), and conclusions are drawn in Section 5 (Conclusions).

## 2 – Basics of Digital Image Correlation

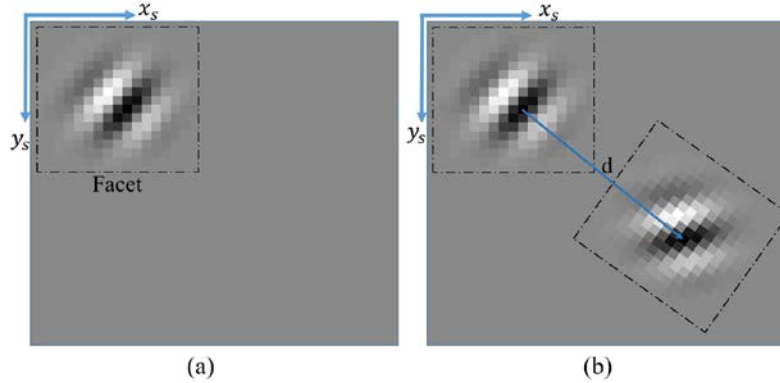
Photogrammetry and vision-based techniques use photographs recorded with imaging sensors to identify coordinates of points, features, and patterns of an object, and use this data to track their motion through different times or stages. This technique was further developed and used for deformation measurement in the early 1980s by Peters, Ranson, Sutton et al. (Peters and Ranson 1982; Peters et al. 1983; Sutton et al. 1983). Through the years, the vision-based systems have proven to be a reliable technique to measure displacements occurring in large-sized structures, evaluating mechanical stress-strain fields, and extracting modal parameters.

Three-dimensional photogrammetry is a non-contact, full-field, optical measuring method capable of extracting surface displacement and geometry profiles from images acquired through a synchronized stereo camera (or multi-camera) system. A generic point  $P$  on the surface of the target object can be represented by its coordinates  $(X_P, Y_P, Z_P)$  in the global coordinate system  $X$ - $Y$ - $Z$  with an origin located at point  $O$ . A schematic of the camera setup is shown in Figure 1. As can be seen, each camera has its coordinate system  $(x_i, y_i, z_i)$  with origin at  $C_i$ , where  $i = 1, 2$  while another plane can be defined in which the projection of the point  $P$  has coordinates  $(x_i', y_i', f_i')$ . This plane, belongs to the image or retinal system  $R_r$  which is obtained as  $z_i$  is shifted by a distance equal to  $f_i'$ , so the point has coordinates  $(x_i', y_i', 0)$  in the image coordinate system. However, since cameras record intensity data at discrete locations (i.e., pixels), another coordinate system named sensor system  $(x_s, y_s)$  is introduced. Therefore, based on the pinhole camera model, three elementary transformations must be performed. The first one transforms the global coordinates of a target object to the camera system coordinates; then, the coordinate is projected into the retinal plane; and finally, it is transformed into the sensor coordinate system in pixel units (Sutton et al. 2009). To sum up, the position of the point  $P$  in the global coordinate system is projected in the retinal plane and measured in the sensor coordinate system as  $p_1(x_{s1}, y_{s1})$  and  $p_2(x_{s2}, y_{s2})$ . Then by combining those two points with the intrinsic and extrinsic parameter of the two cameras, a 3D coordinate of the physical point  $P$  can be obtained using the triangulation theory (Luo et al. 1993).



**Figure 1.** Schematic of stereo imaging setup for 3D-DIC: reference planes and pinhole camera model transformations (Sabato and Niezrecki 2017a).

To perform a DIC measurement, a stochastic pattern (e.g., black dots on a white background or white dots on a black background), must be applied to the surface of interest and the relative position of each of them is tracked as the surface deforms over time. Each image can be considered as a matrix of natural integers where white pixels have a grayscale level equal to 0 and black pixels grayscale level 100. Since a single value is not a unique signature point, a neighborhood of pixels are used (i.e., facets or subsets). Each facet is a set of distinctive correlation areas defined across the measuring region. These facets are typically squares with sides of 10-50 pixels; thus, a facet will typically include several dots (e.g. gray level variations) of the pattern applied to the structure. An example of a structural deformation and facet is shown in Figure 2. The center of each facet can be considered a measurement point. The position of these facets spanning the field of view is tracked through each of the successively acquired images, and the 3D coordinates of the entire area of interest are calculated at each individual facet. The fundamental principle of DIC is to match the same physical point between a reference image and several deformed stages based on grayscale variations of continuous patterns. This process is shown in Figure 2 for a more straightforward understanding. Here, the square facet with unique features is used as a reference image, while a correlation function is used for searching the corresponding facet and defining a displacement vector  $d$  as the specimen moves or deforms (Chu et al. 1985; Kahn-Jetter and Chu 1990).



**Figure 2.** Gray level variations on a structure with a facet and coordinate system: (a) Reference stage, representing the original position; (b) Deformed stage and displacement vector shown in relation to the original position. The structure (facet) has translated horizontally and vertically and has rotated (Chu et al. 1985; Kahn-Jetter and Chu 1990).

Similar to the 3D-DIC, the 3DPT technique measures the 3D displacement of discrete points by tracking optical targets or fiducial markers that are placed on the structure. The 3DPT method is not a full-field measurement technique because it measures 3D motion at discrete points; however, for all practical purposes, it can be considered full-field because it is relatively easy and inexpensive to mount numerous optical targets to cover the structure of interest. The centers of those markers are typically found using an ellipse finding algorithm, and the coordinates of the points in space are identified using a triangulation technique (Luo et al. 1993).

Before performing stereo-photogrammetry measurements, the position of the cameras relative to each other and the distortions of the individual lenses must be determined. To obtain this information, a calibration process needs to be performed by taking several images of an object containing optical targets whose positions are previously well-known (Schmidt et al. 2003a; Schmidt et al. 2003b). Calibration is performed on the cameras' useful measurement volume to obtain the radial distortion coefficient together with the extrinsic and intrinsic parameters for each vision system. The most straightforward technique used for calibration purposes only requires the camera(s) to observe a planar pattern shown in at least two different orientations (Zang 2000). Calibration for a field of view up to ~2 meters is typically performed by taking several pictures of National Institute of Standards and Technology (NIST) - traceable

calibration objects (e.g., panels or crosses) containing optical targets (i.e., dots) whose positions are previously well-known. This information is required for computing the three elementary transformations needed for the pinhole camera model to obtain the 3D coordinate of any physical point using the triangulation theory. Then a photogrammetry process known as bundle adjustment is used to establish the precise relationship between the two cameras. Once a system is calibrated, the relative position of the cameras must not be altered. Otherwise, measurement errors will occur. If the dimensions of the targeted object increase, a more complex calibration procedure needs to be performed (i.e., large-area calibration) (Poozesh et al. 2017). Once calibration is performed, camera pair image measurements can be made on a structure of interest. The simultaneously recorder pair of images can be taken at a rate that is specified by the end user, which can be on the order of milliseconds, minutes, hours, days, or even years apart. Therefore it is possible to monitor how a structure changes over time enabling the use of 3D-DIC for SHM and NDE.

### **3 – Non-Destructive Evaluation and Structural Health Monitoring using Digital Image Correlation**

Photogrammetry techniques have been investigated for assessing the structural integrity and the condition of engineering systems. They have proven to be practical approaches that can be used to evaluate the state of structural health and identify damage before in-service failures occur. In this section, a description of the principal NDE and SHM applications of DIC is presented. The chapter provides a broad summary of the work done by numerous researchers, but is not meant to be an exhaustive list. Research efforts performed in the last few decades are divided based on their domain of use (i.e., aerospace, civil, energy, materials, vibrations, and other) for a better classification.

#### *3.1 – NDE and SHM using DIC in Aerospace Applications*

Structural health monitoring and non-destructive evaluation of aerospace structures are critical due to the need to ensure safety. In this section, a description of the applications of DIC for monitoring the dynamics of aerospace structures and for damage detection in them is presented. Then, an overview of the application for measurements on rotors is summarized.

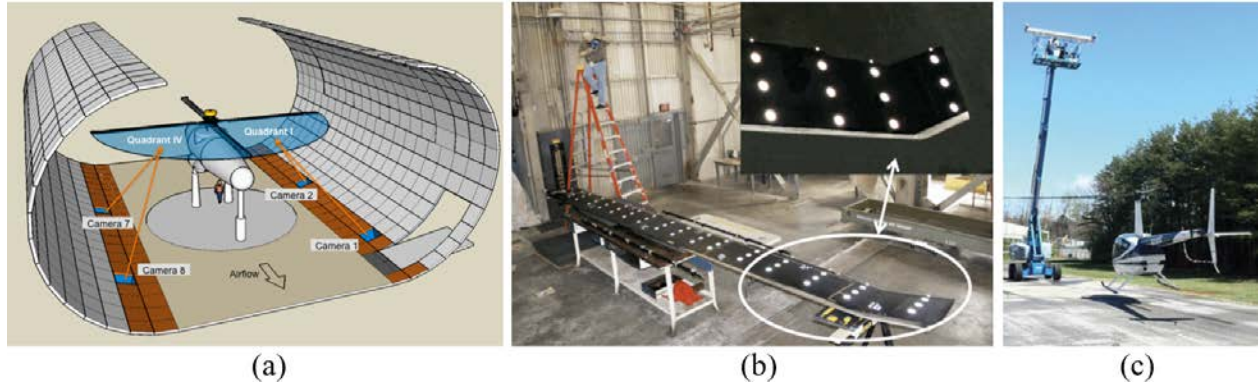
The DIC technique was used by NASA to evaluate the structure of a helicopter in a crash (NASA 2009). A similar measurement was performed later by NASA on another helicopter (NASA 2017). One of the attempts in

detecting the damage retrieved by a helicopter fuselage as a result of different loading conditions and dynamic maneuvers using 3D-DIC and dynamic photogrammetry (DP) was performed by LeBlanc et al. (LeBlanc et al., 2010). The test was performed on a 1:8 scale replica of an Agusta A109 helicopter and demonstrated in the laboratory the ability of DIC to measure changes caused by an added mass in the fuselage area of the aircraft, damages induced by a hard landing, tail loading, and a cracked vertical stabilizer. 2D-DIC combined with the multi-point over-deterministic method was used for characterizing the strain field around a crack propagating in a commercial aircraft wing-skin test panel during a fracture test (Du et al. 2011). The analysis of the more than eight hundred images confirmed both the capabilities of the optical-based technique and provided new insights into the fracture behavior of aerospace components with stiffeners and access holes. Photogrammetry proved capable of tracking the changes in the direction of the crack propagation, its width, tip velocity (i.e.,  $0.014 \text{ mm}\cdot\text{s}^{-1}$ ), and variation of the mode I stress intensity factor from measured displacement fields as increasing monotonic loadings were applied. DIC was also used to validate the assumption that reinforcement systems embedded in the panel provided very high resistance to crack growth.

DIC is a robust technique for measuring dynamics of rotating structures because it is non-contact and does not need wiring. Thus, it has been used by many researchers to monitor the dynamics of rotorcraft blades.

In 2005, a four-camera stereophotogrammetry system was used to collect flapwise, edgewise, and torsional data on a 4-meter, four-bladed rotor system operated within a low-speed wind tunnel (Schneider 2005). The work also describes efforts to accurately determine the center of rotation and transform the coordinate system from the wind tunnel coordinate system to a more convenient rotor coordinate system. In 2010, researchers from NASA performed a similar DIC test on a UH-60A four-bladed rotor system manufactured by Sikorsky Aircraft Corporation (Olson et al. 2010) (see Figure 3a). Two-inch diameter retroreflective targets were used for image acquisition and shape extraction (see Figure 3b) on a helicopter rotor blade. Five operating shapes of the blades were determined in the test.





**Figure 3.** (a) Test section schematic showing camera locations and helicopter tested in the study by Olson et al 2010; (b) Detail of the blade with 2 inch diameter retroreflective targets (Olson et al 2010); (c) 3D-DIC measurement of a hovering Robinson R44 helicopter (Lundstrom et al. 2016).

In 2012, stereoscopic DIC was used in a laboratory environment to obtain the deformation of reduced-scale rotating helicopter blades with the rotor diameter of 24 and 39 inches respectively (Sirohi and Lawson 2012). In this study, the images were captured using a pair of 2-Megapixel cameras recording with a 29.5 Hz operation speed. A commercial DIC software was used to extract the bending and torsion shapes of the blades rotating at 1500 and 1800 RPM and five different pitch angles. Lundstrom et al. used the stereophotogrammetry and 3DPT to monitor dynamics of a Robinson R44 helicopter rotor and to extract its operating deflection shapes (ODS) (Lundstrom et al. 2013; Lundstrom et al. 2016). In this test, the operating data from the blade of the helicopter ( $\sim 10$  m diameter with a tip speed of  $215 \text{ m}\cdot\text{s}^{-1}$ , and a rotational frequency of 6.8 Hz), were captured using high-speed cameras as the aircraft was hovering (see Figure 3c). The research demonstrates that the stereophotogrammetry technique could be used to monitor the flapwise dynamics of the rotor, and extract its harmonic and nonharmonic operational deflection shapes using the power spectra calculated from the acceleration. Another attempt to measured dynamics of blades was performed when cameras were mounted to rotate with the blades. These cameras have their own batteries and can be controlled using a wireless system (Stasicki and Boden 2009). It has been shown that the operating data and ODS obtained using DIC can be used to monitor the structural motion of rotating helicopter rotors.

### 3.2 – NDE and SHM using DIC in Civil Applications

Because of their large size, civil engineering structures are challenging to be monitored using wire-based sensors. Optical systems offer an alternative to the conventional sensors because they allow for performing measurements without interfering with structure functionalities and can reach areas difficult to access without specialized equipment (e.g., trucks, scissor-lifts, and scaffoldings). In this section, an overview of DIC applications for civil structures is presented.

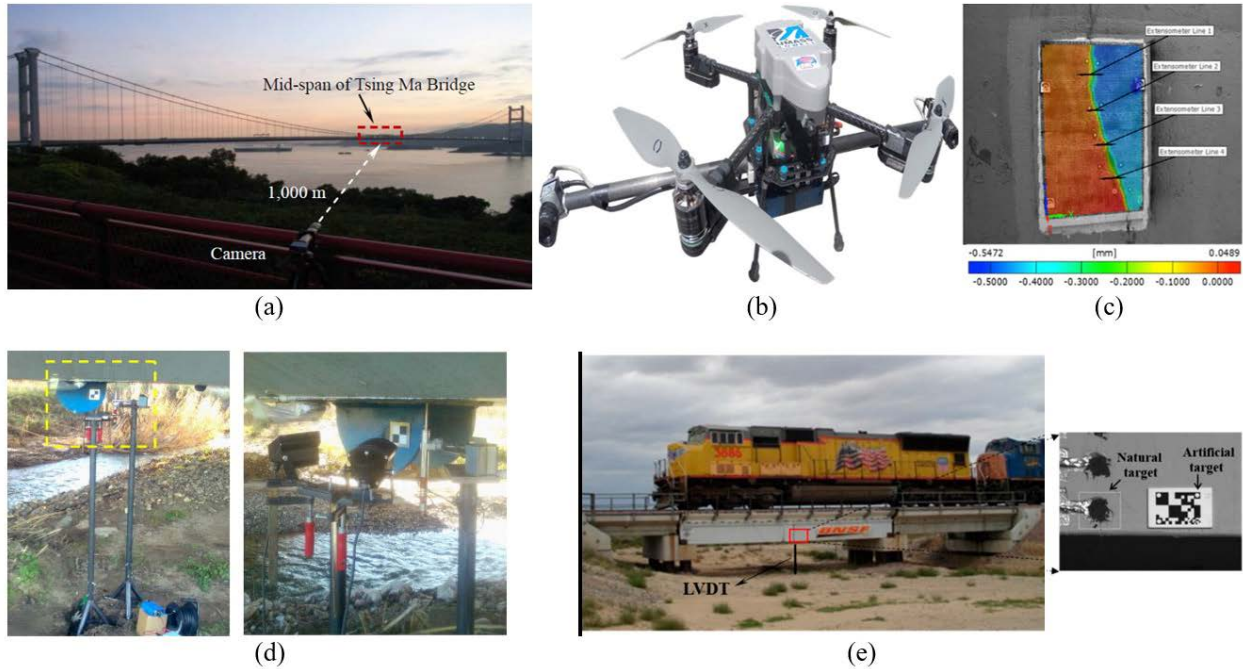
### *3.2.1 – Bridges*

Bridges are among the most monitored civil structures due to their strategic importance and safety issues. The use of computer vision methods to study the dynamic characteristics of bridges and to assess their health status goes back to 1999. Olaszek proposed to use photogrammetric principles for real-time monitoring of the displacement for a point on a bridge. By using a charge-coupled-device (CCD) camera with a telephoto lens, he measured the displacement of a target (i.e., a black cross on a white background). His vision system was equipped with an additional reference to decrease the sensitivity to vibrations (Olaszek 1999). One of the first studies performed to apply optically-based techniques for damage detection and SHM was the work by Fu and Moosa in 2002. In their research, the authors compared the results of measurement performed with CCD cameras with dial gages and laser devices to prove that cameras could be used for measuring structural displacement (Fu and Moosa 2002). Analogously, Lee and Shinozuka, in 2006, proposed and validated a target recognition algorithm to measure the dynamic displacement of bridges in real-time using images. They validated the technique using shaking table tests and an open-box girders bridge. The laboratory tests showed that the proposed system was able to measure displacements with an accuracy less than 3% error in maximum values when the measurement was compared to those recorded using a linear variable differential transformer. In the field applications, the displacement measured by the proposed system showed close results to the laser vibrometer used for a back-to-back comparison with small measurement noise. The main difference of this work to the previous studies was the use of consumer-grade cameras with no specially manufactured optical devices and the absence of an off-line sophisticated signal processing algorithm (Lee and Shinozuka, 2006). Following that, in 2007 Yoneyama et al. used DIC to monitor the variation of vertical deflection of bridge girders. In their research, a bridge was loaded by a heavy cargo truck, and the images of the bridge girder surface were recorded by a single digital

camera before and after deformation. The results showed that deflections obtained by DIC agree well with those recorded by transducers. Moreover, results from other tests performed showed that the bridge's deflection could be measured even when the random pattern was not applied, and only features on the surface of the tested object were used (Yoneyama et al. 2005; Yoneyama et al. 2007). In 2009, Zaurin and Catbas, integrated video images and sensor data to obtain unit influence line (UIL) as an index to monitor bridge behavior under identified loading conditions. Although this work is not entirely related to DIC, it showed another aspect of using vision-based methods by integrating computer vision techniques and sensor data to gain information for damage detection and condition assessment for decision making (Catbas et al. 2011; Zaurin and Catbas 2009; Zaurin and Catbas 2011). In 2010, Malesa et al. compared the performance of DIC with a FEM to measure the displacement of a railway bridge. To reduce the computational power of the DIC algorithm, the researchers implemented a custom-built software package that also considered a normalized correlation metric for outdoor measurements under changing lighting conditions. During the tests performed to validate the proposed methodology, the displacement of optical markers was recorded with a single 1 Megapixel camera as a locomotive was passing at different speeds through the bridge (Malesa et al. 2010). In 2011, Chiang et al. developed two DIC computer codes (i.e., DIC-c and DIC-s) and validated their performance by measuring the vertical displacement of a three-span highway bridge by using three individual marked plates, spaced at 5 meters when a full-size truck was passing by the measurement point. In the tests, a user-grade camera installing an AF18-270mm lens located 50 meters away from the bridge was used. Results showed that the proposed system was computationally demanding since it was capable of obtaining the displacement field of a 1 Megapixel image within an hour at a resolution of  $1/8 \times 1/8$  pixel (Chiang et al. 2011). In the same year, researchers at the University of New Hampshire conducted laboratory and field experiments to validate the possibility of using DIC for measuring the vertical displacement of a three-span continuous steel girder bridge and a short concrete slab culvert with a fiber reinforced polymer retrofit. A comparison between the results from DIC and LVDT sensors showed that DIC results were within 0.03 mm of LVDTs. Also, DIC data was used for model verification in the study (Peddle et al. 2011). In 2012, Busca et al. proposed to use a Canon consumer-grade camera equipped with a  $1920 \times 1080$  pixel sensor and three different levels of zooms to measure the displacement of a 50-meter long steel trussed bridge crossing a river as trains traveled at low speed over it. During these tests, optically-retrieved data was compared with those

obtained from a single point laser interferometer scanner and a wire potentiometer placed in the mid-span of the bridge. The camera was located nearly 100 meters away from the target object, and three resolution levels were used for tracking the displacement of optical targets deployed on the bridge's trusses. In this test, the higher level of zoom was capable of producing more accurate results (i.e., 0.3 mm/pixel); however, it created a smaller FOV, which was of less interest as the full-field response of the structure needed to be analyzed. A strong agreement was shown between the data recorded using the DIC method and the laser even with a low level of excitations (e.g., after the train's passage). Moreover, the optical system was able to detect the first vibration mode of the bridge around 5 Hz. This research also showed the robustness of the method in the case in which no optical targets were deployed on the test structure. In this case, researchers worked on the image contrast between the main beams and the sky. Despite the fact that this approach provided less accurate results, the oscillatory behavior of the bridge was still captured in the measurement (Busca et al. 2012). Moreover, it was shown that measurement reliability is strongly improved by the structure texture contrast. The same group of researchers also proposed a comparison between three different image processing algorithms (i.e., edge detection, pattern matching, and digital image correlation) to estimate the vertical deflection of the same railway bridge subjected to train pass-by (Busca et al. 2014). In 2013, Ye et al. developed a vision-based dynamic displacement measurement system with digital image processing technologies. The researchers used a high-resolution industrial CCD digital camera and an extended-range zoom lens capable of capturing the digital images of a target on the structure over one thousand meters away to trace and identify the displacement of a targeted structure with the aid of pattern matching algorithms. The proposed system was validated with both laboratory tests using well-known excitations and an in-situ experiment to measure the mid-span vertical displacement of the suspension Tsing Ma Bridge (see Figure 4a) and the cable-stayed Stonecutters Bridge during operational conditions. The developed system showed robust capability of long-distance remote displacement measurement and a good agreement between the optically-based measured vertical displacements and those measured using a GPS system located on the first bridge. In addition, the vision system was able to measure the vertical displacement influence lines of the bridges under different loading conditions (Ye et al. 2013). In the same year, Kohut et al. compared the performance of DIC and radar interferometry (RI) in measuring the deflection of civil structures. They compared the displacement field of a steel viaduct subjected to an operational load due to tram traffic. While the RI system used a set of reflecting elements

for performing the measurement, the DIC uses a single camera located ~28 meter away from the bridge to record the position of a plate with a speckle pattern on it. In order to obtain a uniform scale in the entire field of view, the lens axis was aimed at a perpendicular direction to the span axis. Performed tests, proved a better stability and robustness to noise for the vision-based system because of, probably, the uncertainty of the points reflecting the RI wave. Moreover, it was noted that the RI was a 1D system, while a single camera was able to provide 2D information (Kohut et al. 2013). In the same year, Koltsida et al. demonstrated the use of DIC under laboratory conditions for small-scale masonry specimens and field conditions for a masonry arch railway bridge under traffic loading. Because of the inherent features of the masonry, an artificial speckle was not required during the tests, as the natural texture of the material's surface has random gray intensity distribution. In these experiments, DIC was used for measuring strain, cracks, and crack openings under increasing loads. Moreover, a pilot test was performed on a four-span masonry arch railway bridge to measure horizontal and vertical displacements and visualize deformation across the surface as trains were passing by (Koltsida et al. 2013). Nonis et al. used 3D-DIC for periodic inspection of concrete bridges to locate non-visible cracks in concrete, quantify spalling, and measure bridge deformation. In a laboratory test, they demonstrated that optical based measurement correlated well with those performed using fiber optic strain gauges during three and four-point bending tests conducted on a concrete beam. Then, they used photogrammetric targets as extensometers to track the opening of joints and cracks over a 4.5-month period and a stochastic pattern to monitor the strain fields over two bridges in service. In the same study, they also used a projected pattern to quantify spalling phenomena (Nonis et al. 2013). The same bridges were monitored for almost one year using 3D-DIC by (Reagan et al. 2017a). The researchers proposed a novel approach that combines the use of an unmanned aerial vehicle (UAV) and 3D-DIC to perform non-contact, optically based measurements to monitor the health of bridges (see Figure 4b). By installing a stereovision camera system on a drone payload, extensive laboratory tests, and long-term monitoring campaigns, they demonstrated the accuracy of this system in detecting structural changes and monitoring the dynamic behavior of hairline cracks and expansion joints over time. Results show that the combined 3D-DIC UAV system was able to perform structural investigations and detect changes to the bridge geometry with an uncertainty on the order of  $10^{-5}$  m. These results outperformed the resolution that can be obtained when visual inspection techniques are employed while improving accessibility (Reagan et al. 2016; Reagan et al. 2017b).



**Figure 4.** (a) Vision-based displacement measurement of Tsing Ma Bridge (Ye et al. 2013); (b) prototype UAV with 3D-DIC payload and (c) observed crack with in-plane full-field displacement contour (Reagan et al. 2017b); (d) Precision optical target and lighting lamps used as part of the advanced video-based system used for monitoring the dynamic displacement of a railway bridge (Ribeiro et al. 2014); (e) Railway bridge dynamic displacement measurement under trainloads (Feng et al. 2015a).

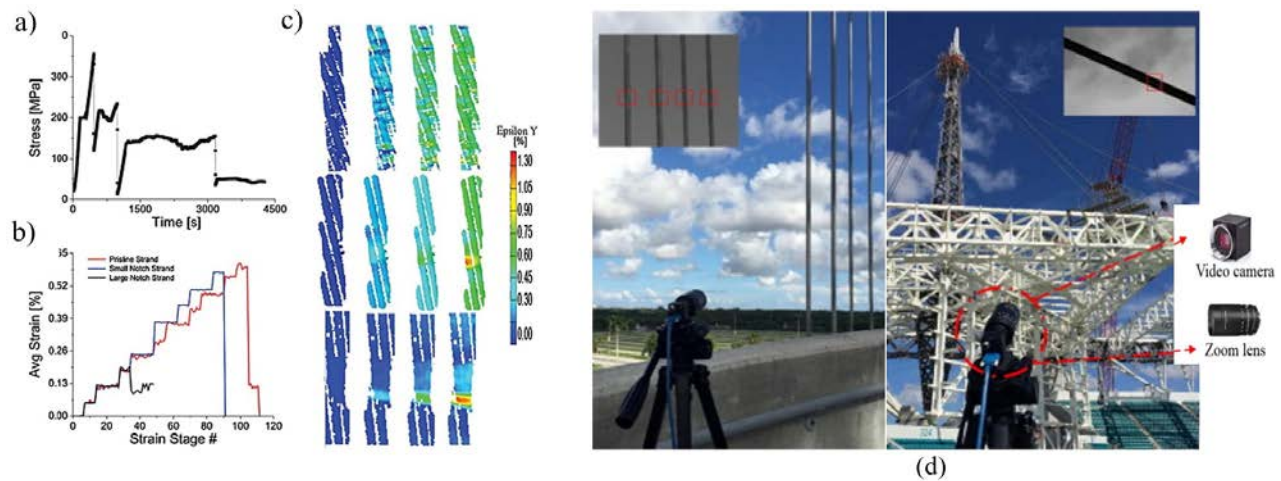
In 2014, Ribeiro et al. developed a non-contact displacement system for railway bridges monitoring based on a high-speed video camera (from 64 fps to 500 fps), an optical lens, lighting lamps, and a precision target. The system was used to measure the displacement of a railway bridge's deck, induced by the passage of trains at speeds up to 180 km/h. Results showed that system precision was below 0.1 mm for a distance of the camera to the target up to 15 meters and nearly 0.25 mm for a range of 25 meters when compared with LVDT data. Findings of their study also proved that the system was sensitive to camera movements, heat waves generated by IR incandescent lighting increased the FOV distortion (Riberio et al. 2014). In 2015 Feng et al., developed an advanced template matching algorithm (i.e., upsampled cross-correlation) for real-time displacement extraction from video images with subpixel

accuracy using Fourier transform. Because of the upsampling cross-correlation method adopted, the system was capable of measuring structural vibrations smaller than 1 mm by adjusting the upsampling factor. The system was validated through extensive laboratory shaking table tests, by measuring the displacement of a high-contrast artificial target attached to the test structure, and in field tests. In this work, the vertical deflection of a railway bridge during train passing was measured, and the frequency domain response of a pedestrian bridge subjected to dynamic loading was used for validating the performance of the proposed system (Feng et al. 2015a). Data recorded using the vision system were also used to validate a Finite Element Model (FEM) of the same railway bridge during the passage of different trains (Feng and Feng 2015). Moreover, the performance of the system was evaluated when low-contrast natural targets or structural features were used as optical markers (Feng et al. 2015b). In 2016, Pan et al. advanced a video deflectometer system using off-axis DIC for real-time measurement of vertical bridge deflection. They used an inverse compositional Gauss-Newton algorithm capable of detecting image displacements in pixels and converted them to physical movements using a calibration technique with the aid of a laser rangefinder. This system, similar to the one proposed by Feng et al. 2015a, is capable of detecting in-plane displacement only because of the adopted pinhole camera model. To demonstrate the accuracy of the system, field measurements of the deflection of a 60-meter three-span railway bridge were performed. The vision-based system proved to be able to measure the dynamic displacement of the bridges, but results were noisy when compared to traditional measurement systems, confirming its sensitivity to various external disturbance (Pan et al. 2016).

### *3.2.2 – Hanger cables*

Another popular application of optically-based measurement for civil structures and infrastructures is the monitoring of bridge hanger cables. In 2008, Ji and Chang were among the first to propose to detect the vibration of the wires holding a small pedestrian bridge using vision systems. By using a commercially available camera, the proposed method analyzed a sequence of images of a vibrating cable and calculated the variation of optical intensity of an arbitrarily selected region of interest to measure the displacement of the wire (Ji and Chang 2008). In 2013, Kim and Kim used DIC to develop an image processing algorithm to analyze images acquired through a digital video camera to estimate tension in the Gwangju Bridge's hanger cables by measuring its dynamic response. The

measurement was performed using only the cable shape and without the aid of optical targets deployed on the structure. In the study, the motion of the vision-based system was also corrected considering a fixed object in the images as a reference point. The results obtained using digital image processing methods and those measured using accelerometer-based methods were characterized by a difference of  $\pm 0.5\%$  for both modal frequencies and tension (Kim and Kim 2013).



**Figure 5.** Bridge cable (a) Stress and average strain curves; (b) full-field strain for the large notch strand; (c) strain visualizations for pristine (top), small notch (center), and large notch strand (bottom) measured using 3D-DIC during a load–unload test performed on a seven-wire steel strands (Vanniamparambil et al. 2013); (d) Vision-based system for determining the tension force in the cable-supported roof structure of the Hard Rock Stadium in Florida (Feng et al. 2017).

In 2013, Vanniamparambil et al. proposed a sensing system combining 3D-DIC, guided ultrasonic waves (GUW), and acoustic emission (AE) to detect breaks on seven-wire steel strands. 3D-DIC was used to identify full-field strain accumulations on the surface of the strands and the notched areas before cable failure (see Figure 5a-c). The results showed that the damage source location could be identified by fusing strain data with acoustics measurement to perform NDE analyses on prestressed and post-tensioned cables found in stay cable bridges (Vanniamparambil et al. 2013). In 2016, Ye et al. employed the multi-point pattern matching correlation algorithm

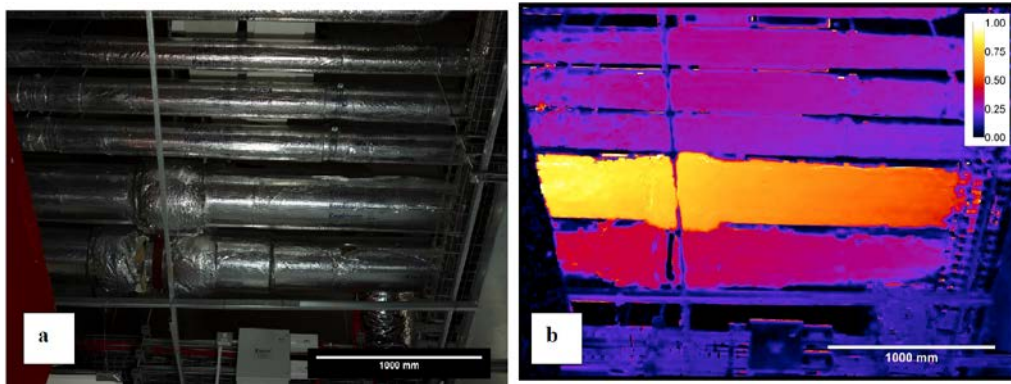


(Ye et al. 2013) to improve a cable force monitoring system. The accuracy of the vision-based approach was validated by conducting uniaxial tensile tests of steel bars, steel wire ropes, parallel strand cables as well as a series of moving loading experiments on a scale arch bridge model. Laboratory tests proved that results obtained with the vision-based system agreed well with those obtained using traditional force sensors (Ye et al. 2016a). In 2017, Feng et al. used a vision-based sensor system, based on the subpixel orientation code matching algorithm (Feng and Feng 2016) to measure the forces acting on the cable-supported roof structure of the Hard Rock Stadium in Florida and ensure that cable tension reach their design values (see Figure 5d). In their tests, the researchers used a 2 Megapixel CMOS-type camera run with a sampling rate of 50 fps. The measured displacement of the cables was used to calculate the natural frequency and evaluate the cable tension. Analyses of the results showed that the measurement recorded utilizing the vision-system was useful in determining the force acting in the cable with a maximum error below 5% when compared with reference accelerometers (Feng et al. 2017).

### *3.2.3 – Other civil applications*

3D-DIC has also been employed for several other applications in the field of civil engineering. For instance, in 2005, McGinnis et al. investigated the use of DIC to measure displacement and strain fields during the use of the hole drilling method to evaluate the state of stress in concrete (McGinnis et al. 2005). The same research group developed an experimental set-up protocol for deploying multiple 3D-DIC sensors simultaneously during the same structural test. The experiments were designed to allow four camera pairs to capture the deformations of key structural components of a coupled post-tensioned shear wall system (McGinnis et al. 2012). McCormick and Lord in 2012 started to explore this technique for monitoring the vibration of cooling water pipelines (see Figure 6) or the movement of the London Eye. What is interesting in this study was the capability of the vision-system to detect displacement relying on the features of the object being tested (e.g., the thermal insulation covering of the pipes) (McCormick and Lord 2012). In 2014, Kohut et al. proposed a vision-based method based on DIC to measure deformations of civil engineering structures under loading condition. The innovation of the proposed approach consisted of three steps (i) image rectification, (ii) displacement field measurement, and (iii) scaling (Kohut et al. 2017). The first step of the method is optional and is performed whether the images are taken from two distinct points in space. In the second

step, the image is divided into intensity patterns. Corresponding patterns are identified on the reference image through the correlation algorithm. The deflection curve is computed as the difference between positions of the similar image patches on two images. Finally, the scale coefficient is calculated from objects with known geometric dimensions. The authors validated their findings by measuring the deflection of a crane under load and comparing the results with those obtained using a laser tracker (Kohut et al. 2014a; Kohut et al. 2014b; Śladek et al. 2013).

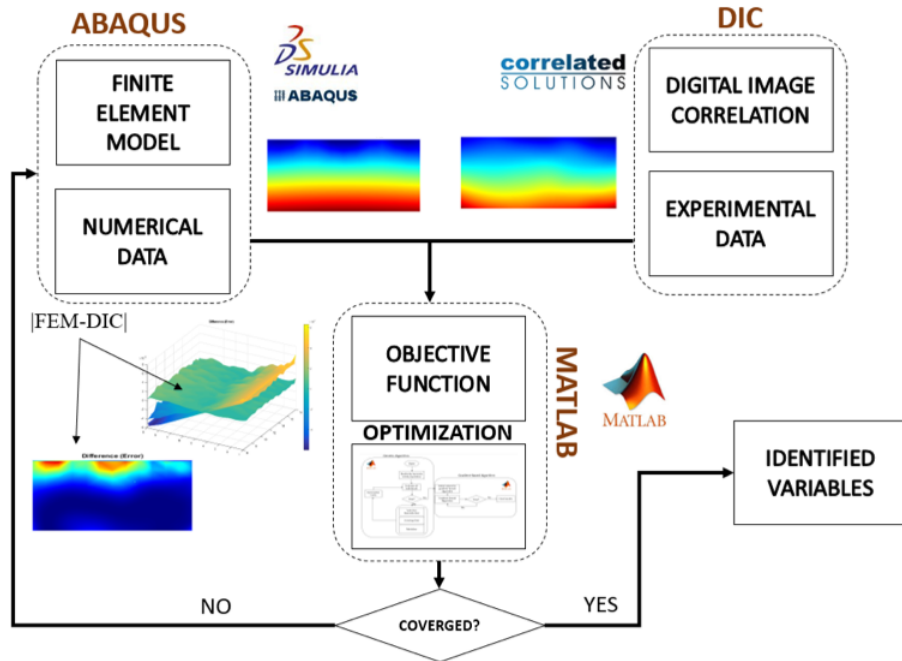


**Figure 6.** 3D-DIC used to detect the out of plane displacement of water cooling pipelines (McCormick and Lord 2012).

In 2014, Murray et al. used four synchronized, 85 mm focal length, high-speed cameras to measure the out-of-track motion of the vertical and longitudinal rail displacement using the texture on the rail itself and tie-mounted targets. The cameras were mounted at a fixed position near the track and away from the train. The proposed system was evaluated at two different sites, one with a high-quality subgrade and one with a peat subgrade, during the passage of eleven trains at the monitored location. Data recorded using the four cameras were used to determine the stiffness and damping of the subgrade and to investigate the factors that influence the magnitude of longitudinal rail displacement (Murray et al. 2014). Sabato and Niezrecki in 2017 proposed another railroad track inspection technique using 3D-DIC. They investigated the feasibility of using optical systems deployed underneath a rail car to assess the deformation profile of railroad crossties for different ballast conditions and under increasing loads. Measurements to validate the proposed approach were conducted using both a painted pattern and a stochastic pattern projected on the crosstie using a projector. Measurements made while using a projected pattern were shown to be equivalent to those

performed as the speckles were painted on the target object. Extensive series of laboratory tests showed that the 3D-DIC system was able to detect out-of-plane displacement as low as  $10^{-4}$  m and with an error of about 3% when compared with a traditional wired, high-accuracy LVDT (Sabato and Niezrecki 2017a; Sabato and Niezrecki 2017b). The researchers also investigated the effect of train-induced vibration on the cameras, demonstrating that an isolation system tuned at about 2Hz was effective in significantly reducing the vibration transmitted to the vision sensors (Sabato et al. 2017b).

Researchers from the University of Virginia, proposed studies to perform an analytical-computational correlation between DIC and FEM. Despite that their research was mainly focused on structural civil engineering applications, their findings can be easily applied to other fields. Dizaji et al. proposed to use 3D-DIC in conjunction with a FEM approach interfaced with MATLAB for structural identification on a large scale specimen (i.e., concrete beam under different loading and boundary conditions). Full field results, obtained through the optically-based method were validated against ground-truth measurements from traditional sensors, and used to update the FEM via a hybrid genetic algorithm that combines a genetic algorithm to perform global optimization in conjunction with a gradient based method as summarized in Figure 7. In their research, the authors used both dynamic and static responses obtained from vision-based measurements to minimize the matching errors between 3D-DIC and FEM, proving that this approach was effective for large scale structural systems (Dizaji et al. 2017a; Dizaji et al. 2017b). The authors also validated the use of DIC to characterize the behavior of concrete across different structural scales by performing a number of experiments (i.e., compression, split tensile, and flexural tests) at both mixture and structural member scale levels.



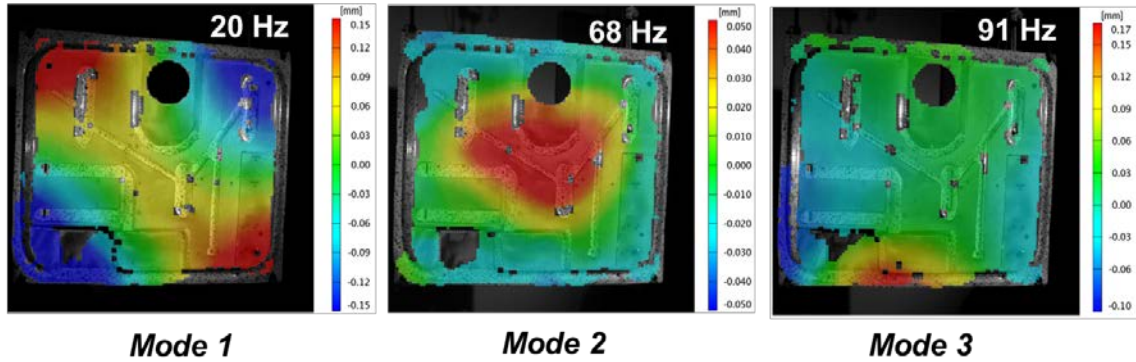
*Figure 7. 3D-DIC FEM integrated approach for structural identification of large scale structures (Dizaji et al. 2017a).*

The work evaluated the performance of two representative plasticity-based numerical models commonly used in stressed concrete characterization (Gheitasi et al. 2018).

### 3.3 – NDE and SHM using DIC in Dynamic Applications

Optical systems are robust alternatives to traditional accelerometers for performing structural dynamic analyses and determining modal parameters of interest in SHM and NDE applications (e.g., mode shapes and structural frequency response). One of the first attempts that used digital image processing for system identification and determining non-linear characteristics of mechanical and structural systems was performed by Chung et al. in 2003. The study demonstrated the proof-of-concept that optical techniques can be used to identify structural characteristics by digitally processing the analog image captured using a videotape recorded during a shaking table test of a model structure (Chung et al. 2003). Following that, Helfrick et al. used 3D-DIC to perform full-field vibration

measurements for damage detection (Helfrick and Niezrecki 2007). In their study, the researchers used 3D-DIC techniques to detect crack across the width of a cast acrylic cantilever beam whose depth was equal to 17% and 40% of the beam thickness. During the tests, the structure was excited using an electro-mechanical shaker at each of its first three natural frequencies corresponding to the first three bending modes of the structure. DIC data was used to calculate the curvature of the beam and polynomial best-fit curves for each damage condition and each excitation frequency. The analysis of the results showed that the optical system was able to detect the presence and location of the damage for the 40% thickness-reduction case using the second and third natural frequencies excitations. For a 17% thickness reduction, the damage index plot derived from DIC measurements contained mostly the same degree of fluctuations as the undamaged condition and was not useful in providing information about the damage (Helfrick et al. 2009). The same authors started to employ 3D-DIC for full-field vibration measurement. They used optically-based measurements for modal analysis to measure the shape and deformation of a vibrating metal base of a dryer cabinet (Helfrick et al. 2008). The study presented results that compared the DIC-measured data with similar tests performed using traditional devices (i.e., accelerometers and a scanning laser Doppler vibrometer) and also a finite element model. The study proved that the displacement measured using a pair of synchronized 4-Megapixel high-speed cameras had a noise floor of  $\sim 20 \mu\text{m}$  when the measurement volume was  $75 \times 710 \times 710 \text{ mm}^3$ . DIC data correlated very well with the other measurement techniques (i.e. accelerometer and laser vibrometry), and the 3D-DIC measurement was able to extract the first three mode shapes of the structure (see Figure 8). The number of points extracted by each approach was significantly different. The modal hammer test extracted information at about 30 points, the laser 313 points, and the DIC measurement had  $\sim 7000$  points highlighting the high spatial density of the DIC measurement. What was also impressive was the time required for performing the data acquisition. In particular, DIC was able to provide results from images recorded for less than one second, while the study reports that the laser measurements took nearly 10 hours to complete, highlighting one of the most significant advantages of optical techniques compared to traditional approaches (Helfrick et al. 2011).



**Figure 8.** Contours of out-of-plane displacement overlaid on a dryer panel using 3D-DIC (Helfrick et al. 2011).

To show the benefits of using optically-based methods for performing high-displacement and low-frequency vibrations measurement, typically difficult to measure with accelerometers and laser vibrometers, Warren et al. conducted a back-to-back comparison between 3D-DIC, 3DPT, 3D laser vibrometry, and accelerometers to measure the dynamics of a structure. In the tests, 3D-DIC and 3DPT monitored the response of a base-upright steel structure at the same eight locations as performed for the accelerometer and laser tests. While DIC can be used over the whole surface, in this case, an alternative approach with discrete patches of patterns was employed to illustrate that equivalent data could be extracted without having to pattern the entire structure. Because of the specification of the cameras used (i.e., 2 Megapixel), working distance (2 m), noise floor ( $\sim 40 \mu\text{m}$ ), amplitude of the displacement characterizing higher frequencies, and ambient vibrations, only the first and third modes of the structure (i.e., 26 and 78 Hz respectively) were captured. Similar tests were performed using 4 Megapixel high-speed camera recording at 500 Hz. Additionally, the displacements determined using 3DPT were used to calculate frequency response functions (FRFs), from which mode shapes were extracted. The results indicate that when low-speed cameras were used in conjunction with forced-normal-mode-testing, both 3D-DIC and 3DPT could accurately capture mode shapes as long as measurable displacements were present. The high-speed optical results were the best obtained in these studies, and the first five modes of the structure (i.e., up to 108.8 Hz) were determined each having a modal assurance criterion (MAC) values better than 99% (Warren et al. 2011b; Warren et al. 2011c).

In 2011, researchers started to use DIC algorithms to estimate the vertical motion of people in a crowd and determine the loads generated by the people jumping on the hosting structures (Caprioli et al. 2011; Mazzoleni and Zappa 2012). In the study, an area correlation matching algorithm and a minimum quadratic difference method are used to analyze two subsequent images recorded by a conventional digital camera and depicting the crowd on stadium grandstands. The study focuses on understanding the effect of different parameters on the measurement accuracy, and it was based mainly on computer simulation. The robustness of the method was experimentally verified by comparing the signal obtained from DIC analyses of a video of a group of people jumping and the signal recorded by an accelerometer attached to one of the people in the crowd. This study paved the road for another study in which the structural response of a major UK stadium was measured (Jones et al. 2011). Using DIC approaches, video of people jumping on the grandstand of the stadium recorded during major sports events were used to determine the forces induced by the crowds and calculate the loads applied to the structure. These forces were then used in simulations involving modal space approximations of a large-scale complex FEM to determine the structural response of the targeted system and the comparisons generated MAC values all above 65%.

In 2014, Wu et al. developed a 2D, 60 Hz sampling rate, vision system to monitor plane vibrations of a reduced scale frame mounted on a shaking table using images recorded by a commercially available digital camera. The study focused on determining the importance of camera parameters, the trade-off between the system resolution and the FOV, and the upper limitation of marker density. In their investigation, to overcome unstable experiment precision due to the scale factor approach used to convert image coordinates measured by a vision system in the unit of pixels into space coordinates, the researchers developed two alternative methodologies: registration and direct linear transformation. The authors processed images using a customized Matlab code to obtain the spatial coordinates of the markers. They demonstrated that motion with frequency up to 20 Hz could be captured and successfully analyzed in time and frequency domains to determine the dynamic characteristics of the targeted structure (Wu et al. 2014).

Bartilson et al. improved the findings of Cigada et al. 2013 by developing a target-less vision system for structural dynamic response studies (Bartilson et al. 2015) to reduce the difficulty associated to the deployment of targets to the test structure, especially in locations critical to access. The main difference of this study with others was

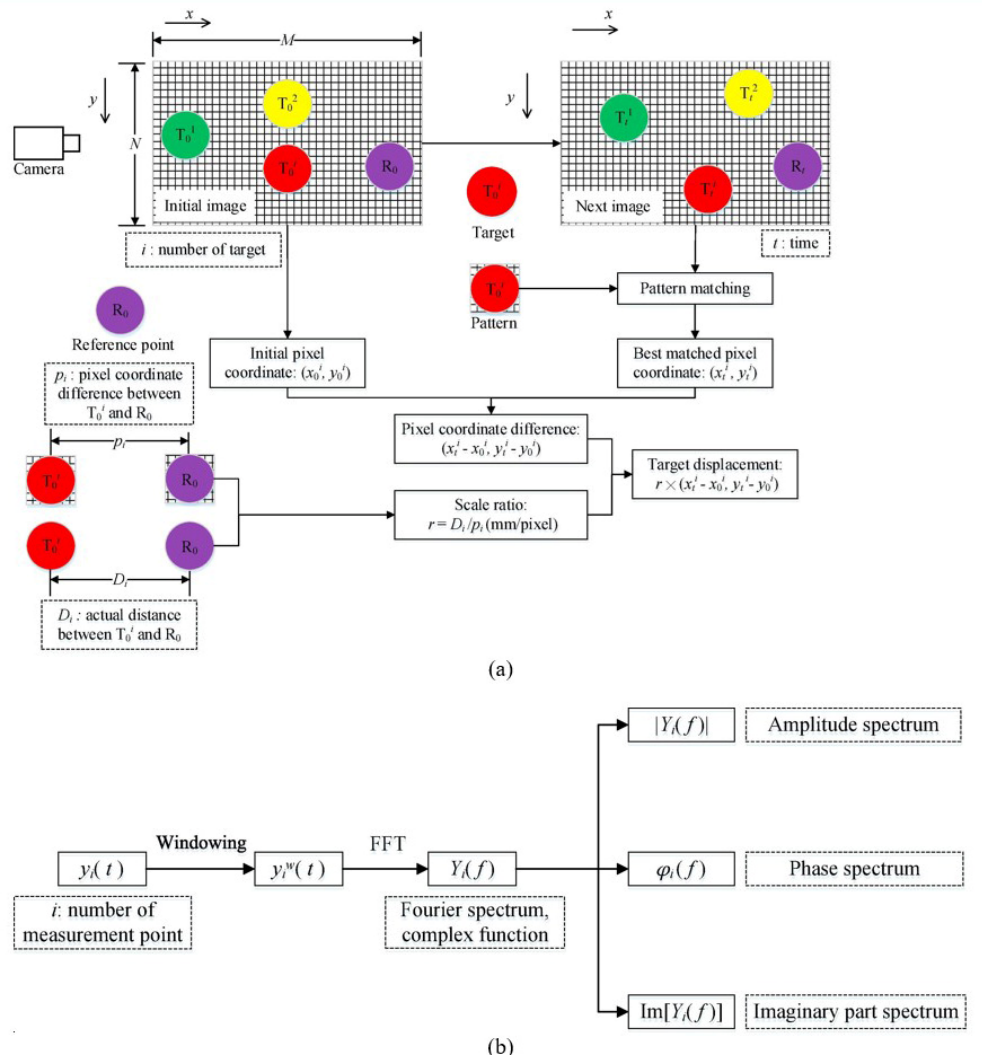
the use of a minimum quadratic difference (MQD) algorithm which was more robust than the previously employed edge detection and cross-correlation algorithms. In this technique, no targets or patterns were placed on the structure of interest and consumer-grade cameras were used. The authors validated their method by accurately determining natural frequencies of a full-scale traffic signal structure with accuracy similar to strain gauges and string potentiometers. By utilizing time series filtering techniques, modal damping ratios were accurately determined, and the mode shapes of displacement reaching only 0.5 pixels were obtained. To continue making optically-based measurement easy to perform, in 2017, Khuc and Catbas proposed a novel approach for displacement and vibration analysis by exploring the possibility of using a new type of virtual markers instead of physical targets. The study suggested a practical camera calibration method to calculate the converting ratio between pixel-based displacement and engineering units and analyzes best practices to consider low contrast, changing illumination, and outliers in matching key points. The method was validated on a four-span bridge model and a real-world structure with excellent results for both static and dynamic behavior of the two structures (Khuc and Catbas 2017).

In the same year, vision-based measured displacement was used to identify structural parameters and external forces. In their work, Feng and Feng aimed to link the measured displacement data to the quantification of the structural health condition of a structure. By using output-only vision-based displacement measurement, the authors validated the feasibility of simultaneous identification of structural stiffness and unknown excitation forces in the time domain. Laboratory tests were performed on a simply supported beam specimen demonstrated that two measurement points by the vision sensor were sufficient for accurately identifying both the beam stiffness and hammer impact forces (Feng and Feng 2017).

In 2018, Dong et al. proposed a method, based on the multi-point pattern matching algorithm, for simultaneous multi-point measurement for structural modal parameters identification using a FFT. A description of the algorithm can be seen in Figure 9. In the study, comparisons with the results obtained by the vision-based system and accelerometers were performed together with analyses on the effect of the distance measurement on the accuracy of the vision-based system, and the feasibility of different types of targets (i.e., LED lamps and black spots). Results of experiments performed on a simply-supported rectangle steel beam model showed how the developed vision-based



system could identify dynamic response and the first two modes of the targeted structure with good accuracy for a distance up to 15 meters with errors between 6 and 14% when compared with a theoretical model of the beam (Dong et al. 2018).



**Figure 9.** Flowchart of the multi-point pattern matching algorithm proposed by Dung et al. 2018 for displacement measurement (a) and time-frequency domain transformation (b) to perform modal parameter identification (Dung et al. 2018).

This section presented a description of structural dynamics potentiality of 3D-DIC and 3DPT. For a complete summary of the state-of-the-art of full-field optical techniques specifically for structural dynamics measurement, the interested readers can refer to (Baqersad et al. 2017; Niezrecki et al. 2010).

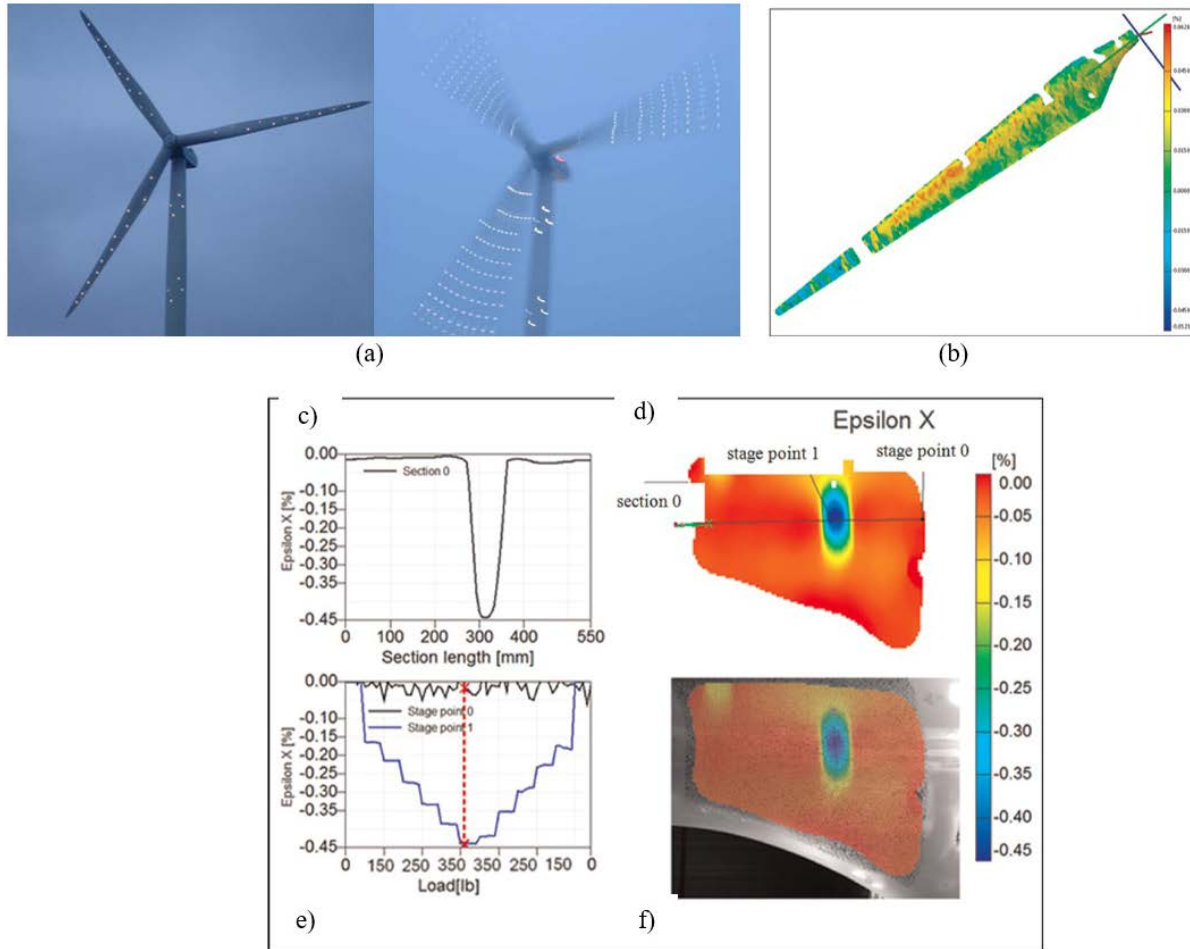
### *3.4 – NDE and SHM using DIC in Energy Applications*

The growing need for clean energy has spurred the widespread use of wind turbines as a valuable alternative to traditional fossil fuels. However, as the size of these machines increases to meet energy demands, wind turbines are subjected to a combination of increased static and dynamic loadings that has an impact on their performance, efficiency, and reliability. Certifying wind turbine blades is an essential part of the design process to verify structural integrity as well as fatigue life. DIC has been demonstrated to be an excellent optical-sensing technology for improved wind turbine blade SHM and NDE.

The DIC technique and its suitability to achieve the SHM and NDE goals of identifying strain amplification or excessive deformation in regions of damage have been explored in several studies. In 2009, one of the first works to use stereophotogrammetry for large wind turbine blades collected dynamic operating data to measure the dynamic behavior of a 500 kW wind turbine during an emergency stop from 24 to 0 RPM (Paulsen et al. 2009). In the same year, researchers proposed a method to use low-speed cameras to measure vibrations in rotating structures by using phase stepping (Helfrick et al. 2009). After that, high-speed cameras were used to estimate vibrations in a small-scale rotating wind turbine, but only a few operating deflection shapes (ODSs) could be determined (Warren et al. 2011a). ODSs extracted from 3DPT data were compared to other rotating tests and a non-rotating modal test. Results indicated a strong correlation between conventional static and optically measured mode shapes. However, some spectral differences were found, and researchers assumed they could be due to changes in the structural boundary conditions present during operation at different speeds. Following this work, Ozbek et al. used retroreflective optical targets to measure the displacement of on a 2.5 MW Nordex N80 wind turbine with an 80 m tower height and rotor diameter (Ozbek et al. 2011; Ozbek et al. 2013a; Ozbek et al. 2013b) (see Figure 10a). Within these studies, the researchers describe the efforts to sufficiently illuminate this massive structure and collect stereophotogrammetric operating data.

The structure was illuminated with high-power light-emitting diode (LED) strobe lights synchronized with the camera pair by a central computer. During in-field tests, the dynamic behavior of the turbine was monitored from a measurement distance of 220 m by using a 3DPT technique and results showed that the deformations of the turbine could be measured with an average accuracy of  $\pm 25$  mm. In the study, it was observed that the measurement error was frequency dependent and mainly caused by calibration problems due to the rotation of the turbine. It was also found that measurement accuracy improved for higher rotational frequencies (i.e., above 1.4 Hz). Also, recorded data were analyzed by using an operational modal analysis algorithm based on the least square complex exponential method and several turbine parameters (Eigen frequencies and damping ratios) were extracted for different wind speed.

Between 2011 and 2013, LeBlanc et al. used 3D-DIC for the full field inspection of a 9 m long TPI Composites CX-100 wind turbine blade manufactured for Sandia National Laboratories. The goal of the study was to extract full-field displacement and strain measurements from a composite turbine blade subjected to increasing static loading (LeBlanc et al. 2011; LeBlanc et al. 2013) (see Figure 10b). The use of 3D-DIC allowed the observing of significant strain amplification in damaged areas, as well as discontinuities in the curvature of the blade at the location of damages. The optically-based technique was able to quantify the progression of damage as the load was applied during laboratory tests, providing more structural information than discrete point-strain measurements (see Figure 10c). Also, a method for combining multiple measured fields of views (FOVs) of the same object recorded moving around the stereovision system (i.e., stitching) was proposed to obtain the deflection and strain over the full length of the 9 m wind turbine blade. It is important to point out that stitching of single geometry and displacement fields is performed by finding transformation matrices that relate corresponding points in the overlap areas. The rotation and translation matrices are computed by using point cloud registration techniques such as Singular Value Decomposition (SVD) or Iterative Closest Point (ICP) (Salvi et al. 2007). In this research, the authors were able to provide displacement and strain measurements over the entire surface of the blade itself by combining 16 FOVs recorded by a single camera and stitched together with photo-editing software, (LeBlanc et al. 2012).

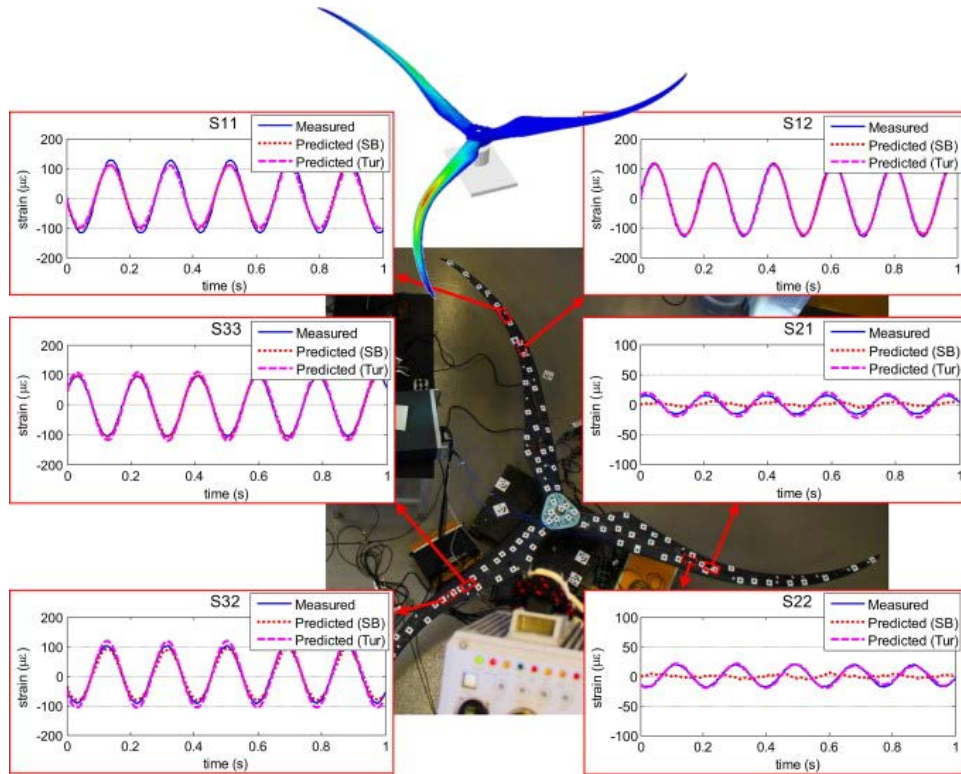


**Figure 10.** (a) Retroreflective targets placed on a 2.5 MW NordexN80 wind turbine used in the study by Ozbek et al. 2013a; (b) Spanwise full-field strain of blade obtained by stitching together 16 independently recorded fields of view as the blade was subjected to a load of 350 lb located 6.75 m away from its root section (LeBlanc et al. 2012). Measurement displaying DIC measurements near the blade root on the the low pressure side for a 400-lb applied static load: c) blade curvature along section line lengthwise of blade (root shown on left), d) displacement contour near blade root, e) strain at points 0 and 1 (shown in b)) as a function of applied load, and f) overlay of displacement contour with blade image (LeBlanc et al. 2013).

Other studies performed on the same 9 m blade embedding defects (i.e. wave defects of well-known geometry inserted at specified locations along the blade length) aimed to compare the pros and cons of different sensing techniques (e.g., DIC, shearography, acoustic emission, fiber-optic strain sensing, thermal imaging, and piezoelectric sensing) as SHM tools for detecting the defects and track the resultant damage due to fatigue testing. DIC measurements were able to reveal the areas characterized by higher levels of the strain compared to the surrounding footprint, revealing the location of the defects. During the fatigue tests, the strain amplification in the vicinity of the fault became more apparent confirming that DIC is an effective method for locating cracks and wave defects on a targeted structure (Niezrecki et al. 2014).

In 2012, researchers proposed to use 3DPT to identify the mode shapes of a Southwest Windpower Skystream 4.7 wind turbine blade (Baqersad et al. 2012). In the study, the blade contained several optical targets, and it was excited at different frequencies using a shaker and a pluck test. The main difference with the research performed by Ozbek et al. 2013a, was the extraction of mode shapes from time domain data. The blade's response was captured using two high-speed cameras, and an operational modal approach was used to extract mode shapes by transferring the recorded time domain data to the frequency domain. Results of the study demonstrated that DIC can be used as an acquisition system for measurement of low-frequency vibrations.

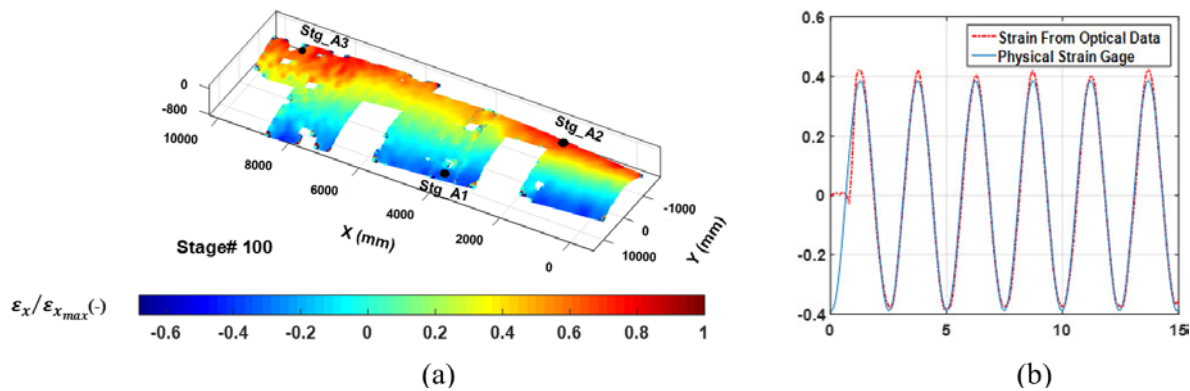
Another set of tests performed on the same Southwest Windpower Skystream blade validated the use of 3D-DIC and 3DPT to predict the dynamic stresses and strains from limited measurement locations using an expansion process in conjunction with finite element models (Carr et al. 2014). In the research, the methods were discussed both during the static and dynamic loadings typical of a wind turbine certification process. In another work, Baqersad et al. studied the use of displacements measured with 3DPT to obtain full-field strain data on the Southwest wind turbine (Baqersad et al. 2015; Baqersad et al. 2016). In their research, measured displacements were transformed to a finite element degree of freedom using a modal expansion algorithm. The expanded displacements were applied to the FEM to calculate the full-field dynamic strain of the structure. The predicted values were compared to measured data by using six mounted strain gages (See Figure 11).



**Figure 11.** Comparison of the strain measured with mounted strain-gages, predicted using modes of the single blade, and predicted using the modes of the turbine for a sinusoidal input at the frequency of the first mode of the blade (5.3 Hz). (Baqersad et al. 2015).

3DPT was used to measure surface displacements for dynamic events and as a complementary set of data for validating the modal expansion algorithm presented in the research. Between 2014 and 2017, Poozesh et al. started developing a multi-camera system for measuring full-field strain and displacement over fields of view (FOVs) larger than those that can be achieved with a single system. The multi-camera system was used during the quasi-static and fatigue tests that are required during the utility-scale wind turbine blade certification procedure required by the International Electro-Technical Commission standard IEC61400-23 (Poozesh et al. 2017). In this study, the authors first evaluated the potential of 3D-DIC in measuring strain and displacement over a large section of a 50-m utility-scale blade subjected to edgewise quasi-static and cyclic loadings. Then, the authors explored the error associated with

using a multi-camera system (i.e., a system composed of two independently calibrated stereo-vision systems) in measuring 3D displacement and extracting structural dynamics parameters on a mock set up emulating a utility-scale wind turbine blade. The idea was validated by performing 3DPT measurements to obtain the displacement fields and operating shapes of a Southwest Windpower Skystream 4.7 wind turbine blade excited using an unknown impact force. Following data collection, the displacement fields were stitched together to reconstruct the global 3D displacement field as a point cloud. The accuracy of the stitching approaches were estimated by comparing the displacement of the overlapped area measured by the two individual systems. Results proved that the time traces for the different targets in the two fields of view were almost identical (i.e., out of plane displacement errors equal to  $\sim 200 \mu\text{m}$  with standard deviations less than  $22 \mu\text{m}$ ). Recently, the approach has been further extended to obtain full-field displacement and strain over a  $\sim 10$  meter long section (Poozesh et al. 2018) and the modal parameters from an analysis of the displacement of a  $\sim 20$  meter long section (Sabato et al. 2018a) of a  $\sim 60$  meter utility-scale wind turbine blade. The obtained results have shown that the proposed system can detect in-plane displacement as low as 2 mm, mechanical strain with an error below 2%, and natural frequencies with an error below 5% when compared with data recorded using traditional wire-based sensors as shown in Figure 12.

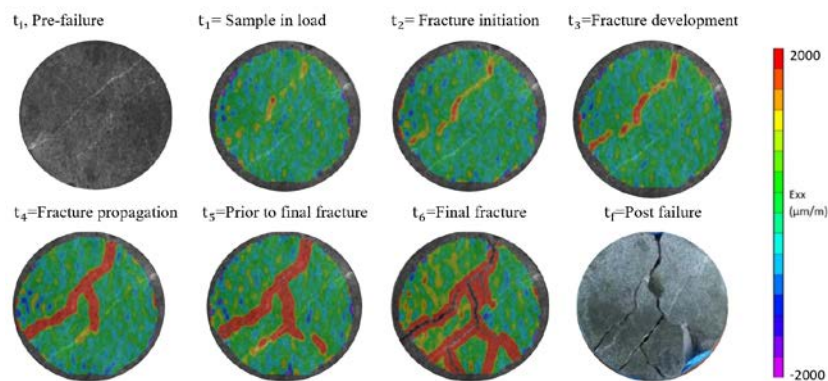


**Figure 12.** Strain results obtained using the multi-camera system for monitoring a  $\sim 10$  meter long section of a  $\sim 60$  meter long utility-scale wind turbine blade: (a) Full-field strain in the Y direction; (b) Comparison of the strain measured with mounted strain-gages (blue lines) and the recorded strain using the multi-camera system (red line) for location *Stg\_A1* (Poozesh et al. 2018).

The stitching approach was shown to be useful for two camera pairs; therefore, in principle, it should be able to be extended to three or more sensor pairs, leveraging the use of optical techniques for analyses on large sized structures.

Besides the use of optically-based methods for wind turbine SHM and NDI, DIC has found applications in other energy sectors too. Hohmann et al. proposed this technique to extend the life of civil structures within nuclear power plants. Concrete degradation (i.e., swelling or shape deformation) of containment building is of primary interest for safety reasons. In their study, the researchers validate the use of 3D-DIC to precisely determine the change of shape and strain in a concrete containment vessel at a nuclear power plant during a pressure structural integrity test (Hohmann et al. 2012).

In 2017, researchers at the University of Louisiana at Lafayette started to apply DIC technique to measure strain development and obtain information about the interaction between natural fractures and induced fractures in heterogeneous rock system (e.g., sandstone sample) for petroleum extraction. The study proved that DIC is capable of illuminating the failure mechanism and strain development in naturally fractured media as shown in Figure 13 (Mokhtari et al. 2017).



**Figure 13.** Strain measurement in heterogeneous Buda limestone with natural fractures at different times and fracturing stages (Mokhtari et al. 2017).



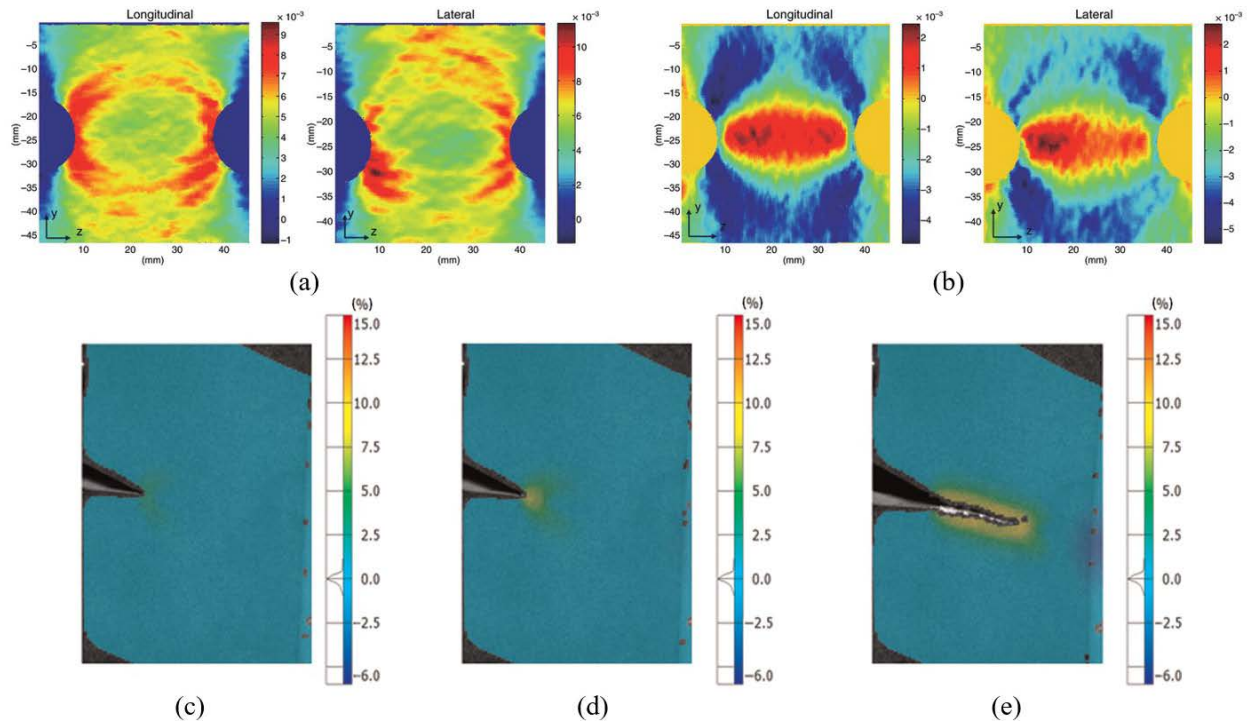
Similar studies were conducted to calculate the strain of elastic rocks and overcome shortfalls of traditional strain measurement. DIC was used to provide information about the strain fields and fracture patterns as different type of sandstones and carbonate formations were undergoing *Brazilian tests*. DIC results were capable of determining winding and erratic fracture initiation and propagation with consistent strain mapping (Nath et al. 2017). These research activities have shown to be promising for petroleum engineers interested in gaining an understanding of the fracturing mechanisms of unusual rock types and their index of brittleness (Parshall et al. 2017).

### *3.5 – NDE and SHM using DIC in Material Testing Applications*

DIC, due to its non-contact nature and the capability to detect displacement at a microscopic scale, has been widely used in testing applications to determine mechanical parameters of diverse materials and experimentally validate the theoretical model of fracture mechanics. In 2002, Abanto-Bueno and Lambros developed a customized DIC code to obtain the in-plane displacement field surrounding a propagating crack, assessing the resistance behavior of functionally graded materials (FGM), and extracting stress intensity factors and resistance curves (Abanto-Bueno and Lambros 2002). The optically-based technique was useful for investigating regions of K-dominance (i.e., areas where the theoretical asymptotic fields describe the near-tip deformation) in the materials and displaying the displacement and strain fields generated by the presence of the crack and from possible rigid body motion. The possibility to refer to full-field strain and displacement maps allowed the gaining of better knowledge about the FGM mechanical behavior under cracking conditions.

In 2005, Lagattu et al, studied the efficiency of DIC for measuring in-plane displacement as high-strain gradients were applied to a composite laminate having a hole in its structure. Results showed that DIC was able to measure increase in strain values up to 12% and demonstrated the efficacy of the method for strain mapping (Lagattu et al. 2005). In 2010, Bernasconi et al. studied the effect of notches and fiber orientation on static and fatigue strength of short glass fiber reinforced (SGFR) polyamide 6. These materials are of great interest in a perspective of a metal replacement for load bearing applications (e.g., automotive industry); therefore, gaining an appreciation on how fiber orientation distribution at notch locations affect strain field is fundamental to understand the fatigue strength and

failure mechanism of the system. In the study, DIC was applied to two specimens, one injected longitudinally and the other laterally. The goal was to measure the strain fields under increasing controlled tensile loading from zero to 5.4 kN, in 300 N steps, highlighting the different mechanical responses for the two selected injection types as shown in Figure 14a and Figure 14b (Bernasconi et al. 2010).



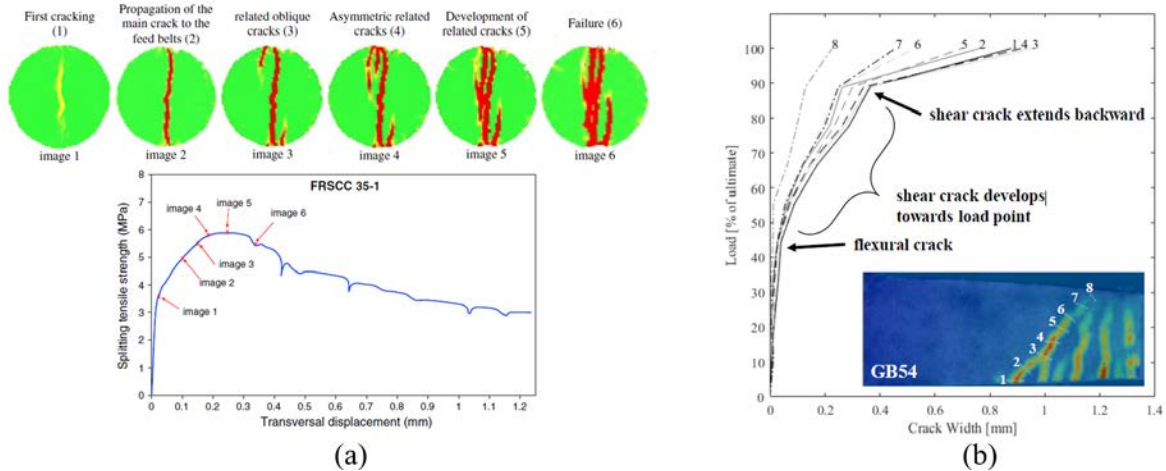
**Figure 14.** Displacement and strain field measured using DIC on a short glass fiber reinforced (SGFR) polyamide 6 with embedded notches (a) Axial displacement fields along y-direction; (b) Transversal strain fields along z-direction (Bernasconi et al. 2010). DIC crack growth for Al 2024 specimens during tensile tests (c) no crack extension, (d) stable, and (e) unstable crack growth (Vanniamparambil et al. 2012).

In 2012, researchers from Drexel University performed a comparison of active GUV, passive AE, and DIC to develop a novel SHM approach based on the combination of real-time optical and acoustic NDT to monitor and quantify crack growth in Al 2024 compact tension specimens. By using data fusion techniques that condensed

information collected using different NDT methods, the authors defined a damage index. The application of this integrated SHM approach resulted in reliable damage detection and quantified crack growth measurements (Vanniamparambil et al. 2012). The same systems were used by Rouchier et al. in 2013 to monitor fiber-reinforced mortar samples during tensile loading tests. In the study, DIC was employed to detect microscopic (i.e., as small as 2  $\mu\text{m}$ ) and macroscopic cracks, and their tortuosity, while image processing procedures were conducted to track their evolution in time over the course of the degradation process (Rouchier et al. 2013). Starting in the same year, researchers from the Ecole Centrale de Nantes experimentally monitored fracture process of concrete structures studying crack opening profiles and crack length using DIC (Alam et al. 2012). The analyses of these parameters are the direct indicators of the local failure in the material microstructure and can completely describe the fracture process of the material; therefore, their analyses were of importance for preventing catastrophic failures. A three-point bending test was performed on geometrically similar concrete beams with different sizes and data recorded continuously using two 2 Megapixel digital cameras with 75 mm macro lenses located at the two faces of the structure. Following that experience, the same group of researchers started developing data fusion techniques using AE and DIC to identify crack openings and size of a fracture zone in concrete. Analyses of the results showed that AE was used to determine the location of fracture growth due to microcracks and macrocracks, however, DIC was able to quantify the dimension of crack openings at various areas of the crack itself. Also, both techniques combined were able to detect the location of the crack tip, confirming that the fusion of the two methods was useful in identifying the fracture process zone and cracking mechanisms of the targeted system (Alam et al. 2014). Other tests were performed on reinforced concrete specimens, crack openings, and crack spacing experimentally measured by DIC and AE were compared with those determined by simulations using Eurocode2. Results showed that DIC provided a very accurate measurement of surface displacement, defining crack openings and spacing, while AE resulted in information about the internal damages caused by the applied service loading (Alam et al. 2015; Alam and Loukili 2017). Similar studies regarding combined approaches and sensor fusion techniques were also proposed by Annamdas et al. 2014 (steel specimens embedding electrode sparked hemispherical defects on their surfaces using a piezoelectric wafer based electromechanical impedance technique and a DIC system for multi-crack monitoring) and Omondi et al. 2016

(control of cracks in concrete structures at laboratory standard tests to characterize the mechanical and damage behavior of prestressed concrete sleepers using AE and DIC).

Concrete and reinforced concrete were among the most studied materials using optically-based techniques. Fayyad and Lees 2014, applied DIC to investigate mode I propagation, crack opening displacement, and crack profiles in reinforced concrete (RC). In the study, the relationship between the fracture properties and the properties of the concrete and steel reinforcement was investigated experimentally performing three-point bending tests on small-scale reinforced concrete specimens. In 2015 Di Benedetti et al. used 3D-DIC to study the mechanical behavior of fiber reinforced polymer (FRP) RC beams during a quasi-static four-point bending tests and comparison with strain gauges and potentiometers. The peculiarity of this study was that two beams patterned with different techniques were used. One using the traditional sprayed speckles, while the other employing computer-generated with randomly spaced speckles with a predefined nominal diameter and laser printed on a transfer paper. Analyses of the results showed that 3D-DIC was the only system capable of measuring out of plane displacement and vertical displacements measured with DIC agreed well with those recorded by potentiometers. Also, strain values in the compression region of the beam were more accurately estimated when the computer-generated speckle pattern was used, while the sprayed pattern was more accurate in the identification of the neutral axis position (Di Benedetti et al. 2015). In the same year, 3D-DIC was also used to investigate the fracture mechanism of steel FRC concrete in a tensile splitting test as shown in Figure 15a (Boulekbache et al. 2015). Other studies involving the use of 3D-DIC for the purpose of gaining additional insight about the development and degradation of shear resisting mechanisms to calibrate a numerical model were performed by Cholostiakow et al. This research also aimed to examine the size effect and overall shear behavior of GFRP RC beams with and without shear reinforcement. 3D-DIC was employed to monitor the crack openings along the shear crack as shown in the example reported in Figure 15b (Cholostiakow et al. 2016; Cholostiakow et al. 2017).



**Figure 15.** 3D-DIC for crack monitoring in FRC concrete specimen: (a) fracture mechanism in a tensile splitting test (Boulekbache et al. 2015); (b) Shear crack width in a FRP RC beam (Cholostiakow et al. 2016).

Considering the increasing use of composite materials such as carbon-fiber-reinforced plastic (CFRP) composites in the aircraft industry, researchers have started to consider scarf-type bonded patches as an alternative mechanical fastened repair technology. Between 2012 and 2013 Caminero et al. used DIC and 3D-DIC to validate the design and certification of repairs carried out in CFRP materials using scarf patch adhesive bonding as the composite plate was subjected to tensile loading. They determined the risk of debonding of the patch under loading in critical stages of the structure’s life. DIC was successfully used to obtain full-field strain measurements in open hole tensile CFRP specimens, highlighting the presence of localized damages and the capability of highlighting strain fields and high strain concentrations around cracks. 3D-DIC was used for performing damage assessment of a scarf repair under tensile loading and comparison with results obtained from Lamb waves analyses, and FEM showed good agreement between the different datasets (Caminero et al. 2012; Caminero et al. 2013a). The same authors performed more investigation on CFRP composites notched (i.e., open-hole) specimens to gain a better understanding of the behavior of mechanical discontinued region that could modify the strength of the material under uniaxial tensile loading. Obtained results confirmed the potential and accuracy of optically-based techniques to study possible damage in laminates with discontinuities and adhesively bonded patch repairs. Nevertheless, this technique still leaves unsolved

the problem of identifying internal faults (e.g., resin cracking, fiber/matrix interface failure, delamination, and fiber micro-buckling.) (Caminero et al. 2013b; Caminero et al. 2014).

Starting in 2012, researchers started to focus on the fracture properties of thin aluminum inclusions embedded in anisotropic paperboard composites and performed tensile tests on non-conventional heterogeneous specimens using DIC for recovering information about the metal deformation and the evolution of the damaging processes leading to the detachment of the inclusion from the surrounding laminate composite (Bolzon et al. 2012). The research included the combined comparison of experimental 3D-DIC measurement and analytical FEM techniques focusing on the out-of-plane displacements that develop in tensile tests as fracture propagates across the paperboard composite and during quasi-static inflation experiments (Bolzon et al. 2017a; Zappa et al. 2017). The same research group performed studies to analyze anisotropic damage mechanisms in forged metal alloy specimens both smooth and notched (Gariboldi et al. 2016), and thin aluminum notched metal foils under uniaxial tensile load (Bolzon et al. 2017b). In the first study, DIC was used to complement the analyses performed using micrograph and was able to gain further information about the strain values on the surface of the notched specimens proving that residual strains were confined to the notch root as well as to the flanges of advanced macrocracks. In the latter, 3D-DIC was used for complementing usual test records, monitoring the displacement distribution, the configuration changes of the specimens, and highlighting wrinkling of the samples during the tests.

In 2017, Asl et al. used 3D-DIC to validate the design of scaled-down wind turbine blades subcomponents made of glass/epoxy materials that emulate the strain field experienced in the full-scale components. 3D-DIC was used to measure the full-field strain distribution and displacement in the bottom flange of the I-beams designed using the similitude theory as the specimen was subjected to a three-point bending test. The measured transverse deflection values were compared to analytical models and FEM simulations (Asl et al. 2017).

### *3.6 – Other applications and vision-based systems*

This section describes the application of vision-based system in areas that are not mentioned in the previous sections.

In 2005, Tong studied the effects of changes in image acquisition conditions (e.g., variable brightness, contrast, uneven local lighting and blurring) to assess the precision of strain mapping (Tong 2005). In 2009, Hutt and Cawley proposed to use 3D-DIC as a cheap and quick testing technique for the detection of structural defects such as cracking and corrosion. The specific case analyzed in the research focused on a crack at a hole in an aluminum plate. Although strain fields were within the noise floor of the measurement, and consequently not detectable by the system, cracks were successfully detected at moderate loads by measuring the displacement discontinuity across the crack itself. In this test, a minimum displacement of  $\sim 0.3$  pixels, cracks of lengths higher than 2 mm, and strain field of 180  $\mu\text{m}$  were detected (Hutt and Cawley 2003). In 2016, Malesa et al presented two different strategies (i.e., for overlaying FOVs and for distributed FOVs) for stitching data obtained from multi-camera 3D-DIC systems. They validated the two proposed approaches by performing monitoring of a 12-meter span graded metal plate hall's arch and an analysis of three individual pipelines in a nitrogen plant (Malesa et al. 2016). In 2014, Zappa et al. proposed a novel technique to reduce DIC uncertainty in dynamic tests due to blurriness caused by a translating target. Despite the fact that this research focused on the 2D case, results can be applied to 3D scenarios as well. In their work, the researchers developed two different methods to simulate the motion effect on a reference image. The first one addressed the issue of sub-pixel shifting using the Discrete Fourier Transform (Reu 2011) to simulate the pure translation of the target; while the second one averages the shifted images to simulate the motion effects. These methods allow the simulation of the acquired images in a real dynamic test and the estimation of the measurement uncertainty caused by the motion effect. Validation performed using harmonic vibration tests, showed that good agreement existed between the experiments and the simulations regarding measurement accuracy modification in dynamic conditions. Also, the authors proposed a numerical technique to evaluate the motion effect present in the acquired images. The method used proved to be capable of reducing bias errors and measurement uncertainties enhancing the performances of DIC in dynamic applications (Zappa et al. 2014a; Zappa et al. 2014b). The same research group, has developed a robust framework for reducing uncertainties of vision-based measurement and evaluated the effects of motion blur. The details of their research are external to the focus of this chapter, but the interested reader can refer to (Lavatelli and Zappa 2016; Lavatelli and Zappa 2017; Zappa and Hasheminejad 2017).

In 2015, Park et al. developed a method to measure 3D structural displacements using a motion capture system that measures the 2D coordinate of a number of markers (e.g., LED lights) with at least three cameras to calculate their 3D coordinates. The effectiveness of the method was tested by comparing the displacements measured in a free vibration experiment of a 3-story structure using both the motion capture system and laser displacement sensors, showing an accuracy of approximately 0.645 mm (Park et al. 2015).

#### **4 – Future Directions**

Optically-based measurement techniques have proven to be suitable tools for SHM and NDE of structures, especially as their size increases. Future directions, to increase the widespread applicability of DIC may involve investigations aimed to develop novel calibration methodologies to simplify the use of stereovision systems as large-sized structures such as long-deck suspension bridges or utility-scale wind turbine blades need to be monitored or measured. Some researchers have already started to investigate in this direction. For instance, Santos et al. worked on developing a novel in-situ calibration methodology for vision sensors to measure the displacement of long-deck suspension bridges where vertical and transversal movements of the deck were on the order of one meter. The minimum requirements for the proposed system consisted of a minimum of two cameras, a set of targets fixed on the structure being monitored, and the knowledge of the distances between those targets to determine the intrinsic and extrinsic parameters needed for the calibration with an accuracy having a standard deviation of two pixels (i.e., in-plane deviation lower than 3.5 mm and out-of-plane deviation smaller than 7.5 mm) (Santos et al., 2012a; Santos et al. 2012b). Based on these findings, the authors proposed an algorithm to perform simultaneously and in real time the vision system calibration and the full motion tracking of large structures. The algorithm showed to be suitable for the estimation of the 6-DOF rotation and translation components of the motion of the structure and the vision system auto-calibration (Santos et al. 2016). Other researchers, proposed to determine the extrinsic parameters of the stereo-vision system by employing sensor board embedding MEMS-based Inertial Measurement Units and Radar systems for calculating the relative position of cameras in space (Sabato et al. 2018b).



Other developments could focus on evolving novel patterning systems. For instance, Mazzoleni et al. proposed a novel toner-transfer technique to impress a well-defined and repeatable speckle pattern on plane and curved surfaces (Mazzoleni et al. 2015), while Park et al. used speckle pattern created by a laser (Park et al. 2018). In 2016, Dworakowski et al. presented a vision-based method based on DIC to measure the deflection curve of a cantilever beam and use those data as an input to a novel detection algorithm based on line segments and voting methods (Dworakowski et al. 2016). Ye et al. developed a vision-based system programmed with three different image processing algorithms (i.e., the grayscale pattern matching (GPM) algorithm, the color pattern matching (CPM) algorithm, and the mean shift tracking (MST) algorithm) for multi-point structural dynamic displacement measurement. The authors validated their approach measuring the displacement influence lines of an arch bridge during a loading test (Ye et al. 2016b). Moreover, interested readers can refer to (Ye et al. 2016c) for a review of vision-based systems other than DIC. Other researchers are starting to explore how DIC can be performed using spectrums of light other than the visible spectrum (e.g. infrared). This would enable patterns to be applied to structures without having to have them be visible.

Volumetric DIC is also another area of research that is currently going through significant expansion. The volumetric measurement relies on scans such as MRIs or CT scans that obtain images at several layers of depth beyond what is shown at the surface. Multiple images are taken in layers to quantify the internal deformation and strain of a material.

As camera technology is improving every year and new cameras are offered at lower prices with better resolution and higher frame rates, the vision-based systems are more frequently used for structural health monitoring and non-destructive damage detection. Likewise, the high computational capabilities offered by new computers can help in applying new image processing techniques for improved damage detection.

Many researchers have tried to integrate finite element analysis with digital image correlation to identify damages. As a future direction, the image processing software packages can be integrated into the finite element software programs. This can enable new algorithms for correlation analysis and to use both numerical and experimental techniques to identify damages in structures.

## **5 – Conclusions**

In this chapter, the development of optically-based techniques such as digital image correlation for nondestructive evaluation and structural health monitoring has been analyzed and surveyed. For nearly four decades, DIC has been improved by many researchers making it an effective and flexible optical technique for surface deformation measurement, geometry profile detection, full-field displacement and strain analysis, and dynamic measurement, from the macroscopic to microscale. This chapter has focused on the measurement aspects of stereophotogrammetry including DIC and point tracking, which are finding new applications every year. The technology has improved significantly over the years with advances in cameras, computational power, and improved computational algorithms. Due to its non-contact nature, the optical measurement approach can overcome the limitations that characterize traditionally wire-based and contact sensors. Moreover, considering the rapid development of optical sensors and computational algorithms, this technique has become a well-established standard technique for static testing and its use rapidly taking hold for dynamic investigations. The possibility to unify multiple fields of view together, combine the optical measurements with autonomous, unmanned approaches, and with finite element models has tremendous potential to provide information and data that could not have been obtained just a few short years ago. These advances and the leveraging of observations of structural features instead of applied patterns, will enable DIC to increase its applicability from simple laboratory-scale testing to structural health monitoring and non-destructive evaluation performed on real-world, large-scale engineering structures.

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