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Non-destructive testing/inspection of composite materials – acoustic impact testing, TV holography and shearography

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English summary

This report provides an introduction to three different non-destructive testing/inspection (NDT/NDI) methods applicable for damage detection in composite materials. A lot of techniques have been developed for metals. However, composite materials often require other techniques, and the damages are often more difficult to detect, due to anisotropic material properties and combinations of materials with different mechanical behaviour and response. More experience is required for inspection and testing of such materials.

The three inspection/testing methods covered in this report are acoustic impact testing, TV holography and shearography. Various techniques within the three categories of methods are developed, and for most of these the physical principle behind and the set-up is described. In addition, it is pointed out what types of damages, defects and material imperfections that may be detected with the different techniques, and what types of damages that are more difficult to detect.

One NDT/NDI method is not able to detect all types of damages. Hence, there is a need for several techniques that can supplement each other.

Sammendrag

Denne rapporten gir en introduksjon til tre forskjellige ikke-destruktive test-/inspeksjonsmetoder som er anvendbare for å finne skader i komposittmaterialer. En rekke teknikker har blitt utviklet for metaller. Komposittmaterialer krever derimot ofte andre teknikker, og feilene er ofte vanskeligere å finne, som følge av anisotrope materialegenskaper og kombinasjoner av materialer med ulik mekanisk oppførsel og respons. Mer erfaring er nødvendig for inspeksjon og testing av slike materialer.

De tre inspeksjons-/testmetodene som er inkludert i denne rapporten, er akustisk anslagstesting, TV-holografi og shearografi. Forskjellige teknikker innenfor disse tre kategoriene er utviklet, og for de fleste av disse er det fysiske prinsippet bak teknikken, samt oppsettet, beskrevet. I tillegg er det pekt på hvilke typer skader, defekter og imperfeksjoner i materialene som kan oppdages, og hvilke det er vanskeligere å finne.

Én test-/inspeksjonsmetode er ikke nok for å detektere alle typer feil og skader. Av den grunn er det behov for flere teknikker som kan utfylle og supplere hverandre.

Contents

1 Introduction

Non-destructive testing (NDT) methods, or *non-destructive inspection* (NDI) methods, are applied to determine the physical condition of an object, performed in a way, so that it is not altering or permanently changing the properties of the object [2]. The main aim of the testing/inspection is to detect damages and defects in the different materials of the object, as well as in the structure as a whole, both during production and from in-service operations. For critical parts of a structure, NDT/NDI hence contributes to maintain a safe use of the object. Applying NDT/NDI methods may in many situations also be very cost and time effective, compared to replacing parts or doing extensive repairs. This latter aspect is a key factor in the maintenance program and the operability of a structure.

Numerous NDT/NDI methods exist, and these can be divided into categories, depending on the physical principles on which they are based. Most NDT/NDI techniques used today belong to one of the following groups [3]:

- Acoustic impact methods
- Thermography methods
- Ultrasonic methods
- Optical methods
- Visual methods
- Radiographic methods
- Magnetic particle methods
- Acoustic emission methods
- Penetrant methods
- Eddy current methods
- Microwave methods
- Ground-penetrating radar methods

The aim of this report is to give an introduction to some of the NDT/NDI techniques that are relevant for composite materials. In the current report, we describe *acoustic impact* methods, as well as *shearography* and the related *TV holography* method, which both belong to the category denoted *optical methods*. Thermography and ultrasound techniques, which also will be referred to in this report, will be covered more thoroughly in a separate and later FFI report. The choice of methods investigated herein is to some extent based on the paper by Kaiser *et al.* [3], in which NDT/NDI methods for examination of carbon fibre reinforced polymer (CFRP) materials are ranked. The selection of methods is also based on the methods relevant for the Norwegian Defence Logistics Organisation and the Norwegian defence industry as part of their in-service maintenance procedures and product development, respectively.

The report is organized as follows: First, a general introduction to some of the different types of defects typically found in composites for structural applications, i.e. sandwich structures and monolithic fibre reinforced polymer (FRP) composite panels, is given. Then, the three above mentioned NDT/NDI methods are described in more detail. For each technique, types of defects that may be detected, and those that are more difficult to detect, are explained. Furthermore, advantages and disadvantages of each technique are discussed. A summary table is provided at the end of the report.

2 Types of defects

Defects and abnormalities in composites can occur both during production and in in-service situations. The source of these abnormalities can generally be related to the materials themselves, such as the mechanical properties of the fibres or the matrix, or the bonding between them. Moreover, deviations from the specifications set for the manufacturing process or the presumed in-service operations may also introduce defects in the composites [4]. Hence, the type and combination of materials used is critical for the overall properties of the composite. A schematic description of some typical types of abnormalities in layered composites, which will be referred to in subsequent parts of the report, is shown in Figure 2.1.

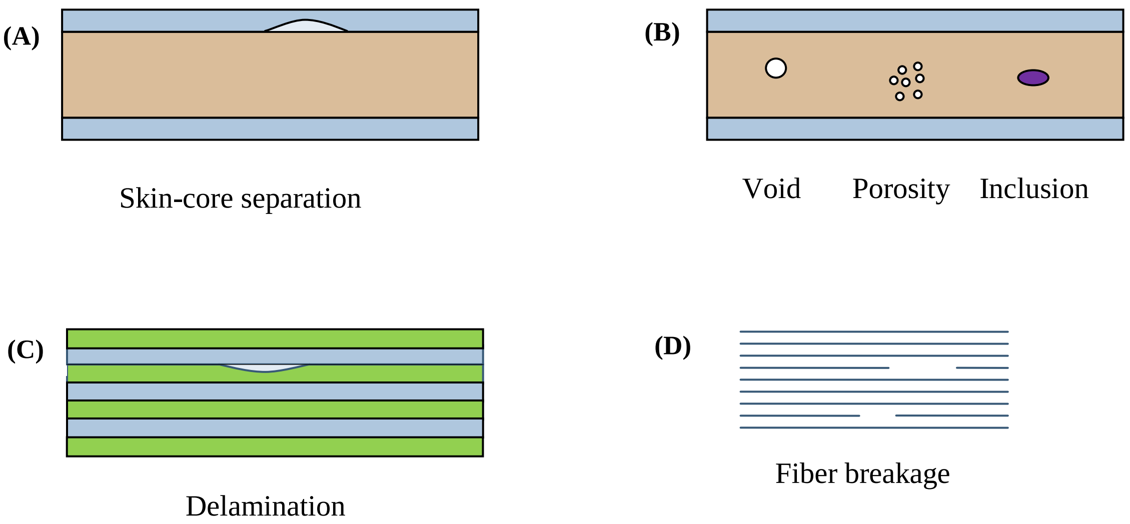

Figure 2.1 Schematic drawing of different kinds of abnormalities found in layered composite structures.
(A) Skin-core separation in sandwich structures is an example of a core disbond. The term disbond is referring to a separation between two (previously) adhesively joined materials. A disbond where the two surfaces are still in contact with each other, or areas where the laminae in a laminated composite are not separated yet, but where the bonding qualities between them are very poor, are termed kissing bonds.
(B) Voids are typically describing air bubbles that are large enough to be individually detected, while porosity is referring to a collection of very small voids that must be detected as a gathered unit. Voids filled with some foreign material, induced during the manufacturing process, are termed inclusions.
(C) Separations between the laminae in laminated structures are termed delaminations.
(D) Fiber breakage in a fiber reinforced composite.

First of all, for fibre reinforced materials, multiple factors of both the fibres and the matrix during the manufacturing process can affect the quality of the produced object. If the fibres are bent in some unintended way, the object will experience a reduction in both tensile and compressive strength [4]. Also, faults, such as local occurrences of enlarged diameter or hollowness of the fibres can lead to elevated stress concentrations, and hence an early failure. Furthermore, factors such as the age of the material, the temperature cycle applied during the curing process, and contamination during the production, can lead to both porosity and voids in the material, as well as poorer bonding quality between the matrix and the fibres. This again can lead to undesired concentrations of internal stresses.

According to Adams and Cawley [4], in-service defects of fibre-reinforced composites can be divided into three main groups. The first is *translaminar flaws*, where the crack propagates across different layers. Such defects are, however, uncommon, as resin rich areas will prevent the translaminar crack growth, and the crack will instead disperse into *delaminations*, also termed *interlaminar cracks*, which is the second group, see Figure 2.1C. This appears to be the most common type of in-service defects for these types of materials. Due to possible air pockets or enriched resin areas, the boundary between two adjacent laminae in a laminated structure is a typical weak spot in the material, and delaminations tend to develop from such areas. Interlaminar cracks do not necessarily affect the tension strength of the object, but they are more critical in compression, where buckling may occur. The third type of in-service damages of fibre-reinforced composites is *transfibrous cracks*, or *fibre breakage*, see Figure 2.1D. This error can reduce the strength of the material dramatically, and hence lead to early failure of the entire object.

For adhesive joints, several sources of defects are possible. Most common are however cracks, voids, porosity or poor curing in the adhesive layer of the joint [4]. In addition, disbonds between the adhesive and the surface of the adherent may also take place. The term *disbond* is here referring to a separation between two adhesively joined materials. A disbond where the two surfaces are still in contact with each other, or areas where two laminae in a laminated composite are not yet separated, but where the bonding qualities between them are very poor, are termed *kissing bonds*. A schematic drawing of common layers in a composite-composite adhesive joint is shown in Figure 2.2.

Figure 2.2 Schematic drawing of the typical layers in a composite-composite adhesive joint. The thickness of the adhesive layer is exaggerated.

3 Acoustic impact testing

Non-destructive techniques using the principles from *acoustic impact testing* is based on the idea that the observable sound registered by knocking, or tapping, on a material, will be a function of the bonding quality between the different components of the structure, as well as the number and location of cracks and inclusions [3]. This implies that the registered sound normally will be altered when there is an internal damage underneath the surface of a composite material, compared to the sound signature of an undamaged composite. Due to the fact that the propagation of sound depends on the density of the material, this method is more sensitive to damages in, or close to the surface [5]. Note that inspection techniques relying on this principle in most cases only provide information about the exact point being investigated, including the area beneath it. Hence, to obtain information about the entire surface of the object, all of its (surface) area needs to be examined [5].

This principle of surface tapping is the basis for several different test procedures. The techniques varies from the basic manual tapping with a coin, to more advanced and automated methods that are using special hammers, which, in combination with computers, analyze the sound response. In the following, three commonly applied techniques using the tapping principle will be described.

3.1 Manual coin tapping

3.1.1 Description

The “original” *coin tapping method* is a manual test where the operator is tapping over the surface of the object with a big coin, or a small hammer, as shown in Figure 3.1. This is one of the oldest and, in principle, simplest non-destructive tests. The operator listens to the resulting sound to find alterations, and hence indications of defects in the underlying material [6]. When tapping over defective regions, with e.g. poor bonding quality, the sound will have more “hollow” characteristics than for the intact areas [3]. In the same way, internal cracks will also change the sound response from the object.

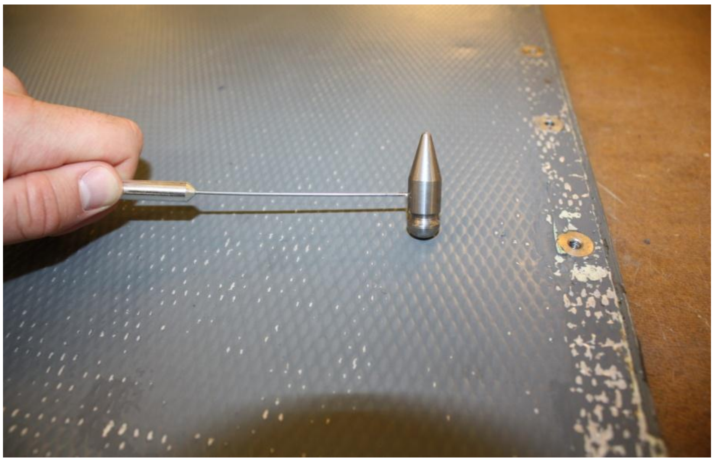

Figure 3.1 Coin tapping. Picture: Norwegian Defence Logistics Organization (FLO).

3.1.2 Types of damages and materials

For sandwich structures, manual coin tapping can detect both delamination in the laminate skins and debonding between skin and core, as these types of damages will alter the responding sound.

Damages that lie deep inside a structure, such as porosity and fibre breakage, may be undetectable with this method, as they give no audible (for the human ear) alteration of the sound [3;6].

According to Kaiser and Karbhari [3], limited research has been conducted on the use of manually coin tapping on CFRP components, so its efficiency or suitability for this type of objects is somewhat unknown. Kaiser and Karbhari indicate that this may be due to the fact that the results of this manual test relay on the subjective opinion, experience and skills of the operator, and that a scientific measurement thus can be hard to obtain [3].

3.1.3 Advantages and disadvantages

The most significant drawback of the manual coin tapping method is, as mentioned above, that the outcome of the test method is strongly operator-dependent [3]. First of all, the sensitivity of the obtained information is generally limited by the sensibility of the human ear. Moreover, the quality of the reported result depends on the operator's level of experience from similar cases, as well as the knowledge of the material properties, the production and repair procedures. Furthermore, the test only gives information about the exact point being tapped. Thus, the entire surface must be examined, which in fact could be a challenging and time consuming task (i.e. when conducted manually).

On the positive side, manual coin tapping seems to be simple, relatively fast and a good supplement to other methods [3]. The only tool required is the tapping hammer (or a set of these for different materials and sound responses). In addition, it does not require any specific areas for performing the examination, such as protective walls, and the method can be applied to both composites and metal structures with any geometric shape and material combination.

3.2 Force-time analysis

3.2.1 Description

The reason for the sound variation when tapping over damaged and undamaged areas is that the actual force applied is altered. In damaged areas, the local stiffness of the material is reduced, giving a longer duration and a lower frequency of the sound [5]. As a consequence, the force applied to the structure is decreased. One way of reducing the operator-dependency and thereby improving the quality of the results from the manual coin tapping test, described in Section 3.1, is therefore to use a hammer that measures the applied force and the duration of the resulting sound [3]. This is referred to as a *force-time analysis*.

A description of the frequency of the sound is obtained by performing a Fourier transformation on the measured force-time relation [5] [1]. Accordingly, areas with a relatively lower frequency, compared to the rest of the surface, will have a higher probability of internal defects being present.

As an alternative to monitoring the force-time relation, it is possible to directly measure the frequency of the produced sound [5]. However, a main disadvantage of this particular procedure is that the results, in the same way as for the manual coin tapping test, will be sensitive to background noise.

3.2.2 Types of materials and defects

The force-time analysis procedure will only detect damages that alter the stiffness of the material, such as debonds and delaminations [5]. As an example, Kaiser and Karbhari [3] showed that delamination in graphite-epoxy composites can be detected by comparison of duration times. However, they experienced problems when trying to detect fibre breakage and fibre misalignment.

3.2.3 Advantages and disadvantages

With a specialized tapping device, the interpretation of the coin tapping procedure is less operator-dependent, compared to the manual variant. However, both force-time relations and frequency spectra still need to be interpreted by an experienced operator [3], and it is still a surface inspection method.

It should also be remarked that the force-time analysis test is insensitive to background noise, which could be a problem in the manual version [5]. Also, the sensitivity of the procedure is depending on the difference in stiffness between the hammer and the material [5], and hence the quality of the results may be device-dependent.

3.3 Mechanical impedance

3.3.1 Description

Measurement of the object's resistance to motion is another method where the principle from acoustic impact testing is employed. This resistance is termed *mechanical impedance* (Z), and can be expressed as the ratio between the force applied to a point F , and the resultant velocity v of the surface at that point [6],

$$Z = \frac{F}{v} \tag{3.1}$$

[1] A Fourier transformation is a mathematical operation that transforms the sound signal input into its associated frequencies.

In the mechanical impedance method, one tries to detect areas in a layered structure where one or more of the layers are separated from the base layers.

In an undamaged area, Z will depend on the contact stiffness between the hammer and the structure as a whole, i.e. all of the material beneath, at the point where the hammer hits. This is indicated by the blue arrow in the left part of Figure 3.2, for an object with perfect bonding between the layers through the thickness. The value of Z in a layered structure *with* defects, will only be related to the material *above* the damage area. This is indicated by the green arrow in the right part of Figure 3.2 for a layered structure with a disbond or void in the glue line/layer interphase. Since the dependent region is changed in the damaged state, compared to the undamaged state, the mechanical impedance will be altered as well. Hence, the change in mechanical impedance can be applied to detect internal defects of this type. A single frequency, typically being between 1 and 10 kHz, is used when carrying out the measurements.

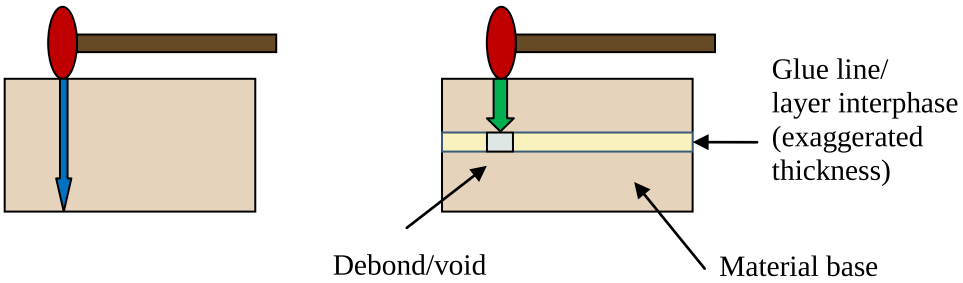

Figure 3.2 The left drawing shows a undamaged area, where the mechanical impedance depends on all of the underlying structure at the point being tapped. In the right hand side drawing, a damage is present, and here the mechanical impedance depends only on the part of the structure that is between the hammer and the damage/debond.

In this procedure, reference values need to be obtained for each new object [6]. The hammer measures the force applied to the structure, and this is used in the calculation of the mechanical impedance. The obtained information can be expressed as a map describing the underlying properties of the surface [6], somewhat similar to an ultrasonic C-scan, see e.g. [7;8] .

The sensitivity of the mechanical impedance method depends on the material of the object and types of defects present. Best results are obtained when the base structure is stiff and the layer above the damage is thin [6;9].

3.3.2 Mathematical modelling

Defects are, as for the coin tapping methods, detected by a significant reduction of the local stiffness of the structure at a given point. Mathematically a defect can be modelled as a spring, where the spring stiffness is depending on the layers above the damage [9]. At a given point on the surface, only the total stiffness k can be measured.

However, the total stiffness is related to the finite contact stiffness, k_c , between the transducer and the object, and to the defect stiffness, k_d , defined by the distance from the damage to the surface. The relation between k , k_c and k_d can be expressed as follows [9]:

$$\frac{1}{k} = \frac{1}{k_c} + \frac{1}{k_d} \quad \text{or} \quad k = \frac{k_c k_d}{k_c + k_d} \tag{3.2}$$

In normal areas, k_d is infinite, and hence $k \approx k_c$. The finite contact stiffness k_c will limit the sensitivity of this test. To obtain a suitable test sensitivity, the order of k_d therefore needs to be lower than the order of k_c .

3.3.3 Types of damages and materials

The method is applicable for detecting defects that lead to a separation, i.e. delamination, between two or more layers in a layered composite structure [9], but it is not usable for revealing transverse cracks in the material [9]. Moreover, mechanical impedance can be employed for detecting disbonds, as well as voids, in adhesive joints.

The capabilities for the mechanical impedance method was thoroughly investigated in the SaNDI project [6]. As concluded in the project report, skin-core separation and local contact damage in sandwich structures, where the size of the damaged area is larger than 50mm in diameter, are detectable with moderate accuracy by the method. Furthermore, this technique is most efficient for detecting damages close to the surface of sandwich structures, but it is not appropriate for detecting damages that are located deep into the core material or close to the back wall of the object.

3.3.4 Advantages and disadvantages

It is relevant in this case to compare the mechanical impedance method to the NDT methods using ultrasound to detect damages and abnormalities. First of all, mechanical impedance has the advantage that it is quite fast and does not require the use of a coupling media between the transducer and the object; most ultrasound methods require a coupling media to be applied. Concerning inspection of honeycomb structures, mechanical impedance has the benefit that the output of the test is less dependent on the placement of the transducer in relation to the damage [9]. This is due to the fact that mechanical impedance uses sound waves with lower frequencies, and hence longer wavelengths than ultrasonic signals. On the other hand, the use of a larger wavelength will increase the minimum size of a detectable defect. As the local stiffness of honeycomb structures is strongly dependent on the bonding qualities between the skin and core, the mechanical impedance can be very effective for studying such structures [9].

One restriction of the mechanical impedance technique is that it can only detect defects that are parallel to the surface of the structure, i.e. delaminations and debonds.

4 TV holography

NDT methods using *classical holography* is based on comparison of double exposed holograms of the object. One of the holograms is from a condition where the object is under stress, while in the other hologram the object is in an unstressed state. The fundamental idea behind this method is that the topology of the surface will be altered when the object is subjected to stress, and that the degree of change will be different in damaged areas compared to undamaged areas. Hence, by comparing the unstressed and stressed conditions, a description of the surface deformation under stress is obtained, displayed as a *fringe pattern*. An abnormality in the pattern could imply a damage inside the object in the given area [10].

Producing holograms is a quite time consuming procedure, and, as an improvement of this method, *TV holography*, often referred to as *Electronic Speckle Pattern Interferometry* (ESPI) in the optical literature, has been developed [10]. In TV holography, the *speckle patterns* of the surface of the object is compared, instead of the holograms. The speckle pattern is the unique combination of dark and bright spots, i.e. the “speckles”, which are obtained when a coherent light is sent to illuminate an optically rough surface [11]. By detecting phase changes numerically in these patterns, the duration and processing time of the method is greatly reduced.

Concerning the list of different types of NDT methods described in Section 1, TV holography is classified as an optical method.

4.1 Description

In TV holography, a laser source with large longitudinal coherence is used. The beam of laser light is split into two separate beams, an *object beam* and a *reference beam* [10], see Figure 4.1. The object beam is expanded by an expansion lens, before it is sent to illuminate the object. The beam will then be reflected backwards from the surface, and sent through a lens. The reference beam is also expanded by a lens. Finally, the reflected object beam is recomposed with the expanded reference beam, and recorded using video image sensors, such as CCD. Due to the fact that the two beams are close to collinear, there will be an interference pattern with spatial periods large enough to be detected by a CCD camera. The interference is producing a speckle pattern of the surface of the object, which then is observed by the CCD camera, and furthermore processed and stored on a computer. The object wave hence provides a deformation map of the object’s surface that can be used for inspections.

The reference beam can, in addition, be sent through a computer controlled reference modulation unit, before it is recomposed with the object beam [12]. With this unit, it is possible to add an artificial vibration or deformation to the signal. This, in combination with numerical algorithms, enhances the quality of the results. A set-up with this modulation unit included is showed in Figure 4.2.

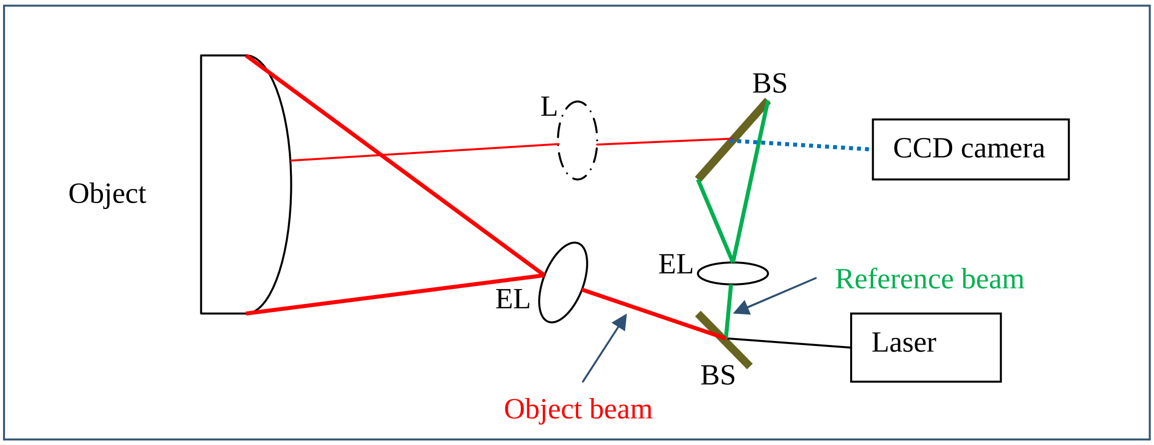

Figure 4.1 Set-up for TV holography. BS: beam splitter; EL: expansion lens; L: lens. The object beam is marked in red, while the reference beam is marked in green. The combining of the two beams, after the last beam splitter (here working as a combiner), are showed as a dotted blue line. Note that a large area of the objects surface is illuminated simultaneously, hence no scanning of the surface is needed.

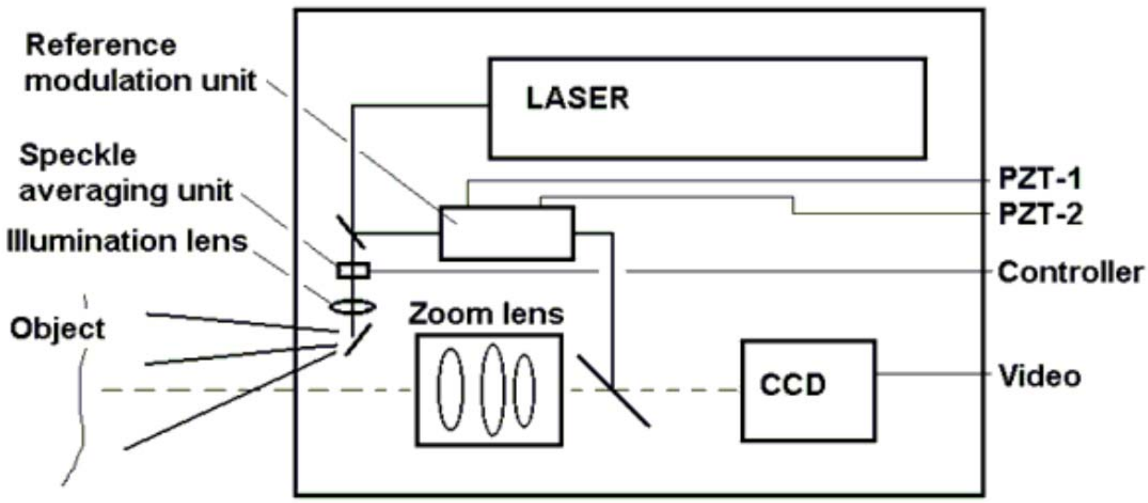

Figure 4.2 Set-up for TV holography. Picture is used with permission from Optonor [12].

During the TV holography inspection, two speckle patterns of the surface are produced and stored on the computer: one when the object is in the unstressed state, and one in the stressed state. When the object is under stress, there will be a deformation of the surface, and hence the path length of the object beam will change, compared to the unstressed configuration. This further implies that there will be a modification of the observed speckle pattern, since the relative phase between the object and reference beam is altered in the stressed state. By subtracting the unstressed state speckle image from the stressed state image, and then taking the absolute value of the result (since only positive value can be displayed in a monitor), the fringe pattern is obtained [10]. A mathematical description, expressed in terms of the intensity of the speckle patterns, is given in Section 4.3.

4.2 Applied load

To obtain the stressed state image, some type of loading must be applied to the object. Possible sources of this induced stress are air pressure, vibration, thermal loading or other kinds of mechanical loading [13]. The purpose of the applied loading is to maximize the change of the surface, to detect internal damages or abnormalities. Therefore, the most efficient type of loading will vary from case to case, among others, depending on the behaviour and properties of both the object and the expected abnormalities.

An appropriate mechanical loading will generally result in excessive movement of the surface. While by such a loading one is able to detect debonds, it will also increase the chance for false positive responses. This is because it is plausible that the undamaged areas of the surface, due to this treatment, will be significantly altered as well. That is, a mechanical loading will produce dense fringe patterns, and it will then be difficult to pick out interior faults from fringe abnormalities [14].

The use of air pressure, which is one special, but efficient, type of mechanical loading, has a lower chance for false positive test results. This type of load is very effective for detecting internal damages, such as subsurface flaws, especially if internal pressure and vacuum chamber is used [14]. With the use of vacuum, TV holography can detect debonds with closed boundary, but not debonds at the edges [15].

By applying thermal loading in the form of heat, debonds and cavities may be detectable by their expansion [14]. This procedure can also detect defects that alter the heat conductivity of the material, and hence adjust the normal displacement of the heated surface. Note that composites, in general, have a relatively low conductivity, and this enhances the possibility for observing such a heat induced pattern in these materials, compared to for example metal; a study of the thermal conductivity of some composite materials has been conducted by Mutnuri [16].

With vibration loading, the object is typically excited sinusoidally [14]. Applied vibration can detect defects inside the object, as they under this type of loading may vibrate stronger than the rest of the material. Note that small damages need a high frequency to obtain an altered resonance frequency, compared to the rest of the material [14]. However, these high frequencies might be hard to detect. The use of vibration as the applied load, is in many cases both faster and easier to perform than using air pressure, heat or other types of mechanical loading.

4.3 Mathematical description

As described in Section 4.1, the speckle pattern for the unstressed and stressed states can mathematically be expressed by the intensity, I. The unstressed state can be written as [10]

$$I = I_o(1+\cos\phi) \tag{4.1}$$

where I_o refers to the object image, and ϕ to the random phase angle due to the optically rough surface of the object. In the stressed state, the phase change Δ is introduced, due to the deformation, and the intensity I' can now be expressed as

$$I' = I_o(1+\cos(\phi+\Delta)) \tag{4.2}$$

The fringe pattern I_f is obtained by subtracting the unstressed intensity from the stressed intensity, and then using the absolute value of the result,

$$I_f = \left|I_o(\cos(\phi+\Delta)-\cos\phi)\right| = 2I_o(\sin(\phi+\frac{\Delta}{2})\sin(\frac{\Delta}{2})) \tag{4.3}$$

This resulting fringe pattern describes the topology of the surface, where the fringes correspond to the contour lines in a map [17]. Abnormalities in this fringe pattern imply possible damage underneath the corresponding areas. Since TV holography is measuring the absolute displacement of the surface, any vibration or other disturbance of the object's position, between or during the two obtained speckle patterns, disturbs the quality of the result.

4.4 Lock-in ESPI

The normal deformation of the surface under stress can hide the altered deformation induced by internal defects. As an improvement of the regular ESPI technique, a new procedure, applying the principles from lock-in thermography [3;18-20], has been developed. This method is termed *lock-in ESPI* [21].

In lock-in ESPI, a computer controlled heat source is added to the regular set-up for ESPI, used to induce modulated thermal excitation into the object. This excitation will lead to a corresponding, modulated spatial alteration of the surface. The regular ESPI set-up is used to monitor these changes, in addition to the induced modulated heat.

As the first step, modulated heat is induced into the object, and a series of images of the effects on the surface is obtained. The processing of these images is then done in two steps [21]. First, a map of the height change of the surface is produced. Second, a Fourier transform analysis is performed on this height distribution, and a description of the height modulation is obtained. Finally, information is employed to establish descriptions of the amplitude and phase distribution. The phase distribution is used to obtain information about the presence of internal defects.

Compared to regular ESPI, lock-in ESPI provides a significant improvement of the *signal-to-noise ratio* (SNR), as well as an enhancement of the *probability of detection* (POD) [21]; POD denotes the method's probability for detecting a given type of discontinuity in the material [2]. By varying the lock-in frequency, it is also possible to perform a depth analysis of the defects [21].

4.5 Types of damages and materials

TV holography is detecting abnormalities by applying the displacement field of the surface under stress. Thus, this method is most suitable for detecting defects in, or close to, the surface; generally it is most efficient for testing of plate and shell structures [10]. The types of defects that are possible to detect with TV holography, extensively depend on the type of applied load. However, defects, such as debonds, cavities and abnormalities that alter the heat conductivity of the material, are commonly detectable.

A set-up for both TV holography and shearography (described in Section 5) is shown in Figure 4.3. The TV holography equipment is, among others, applied for inspection of composite shell structures.

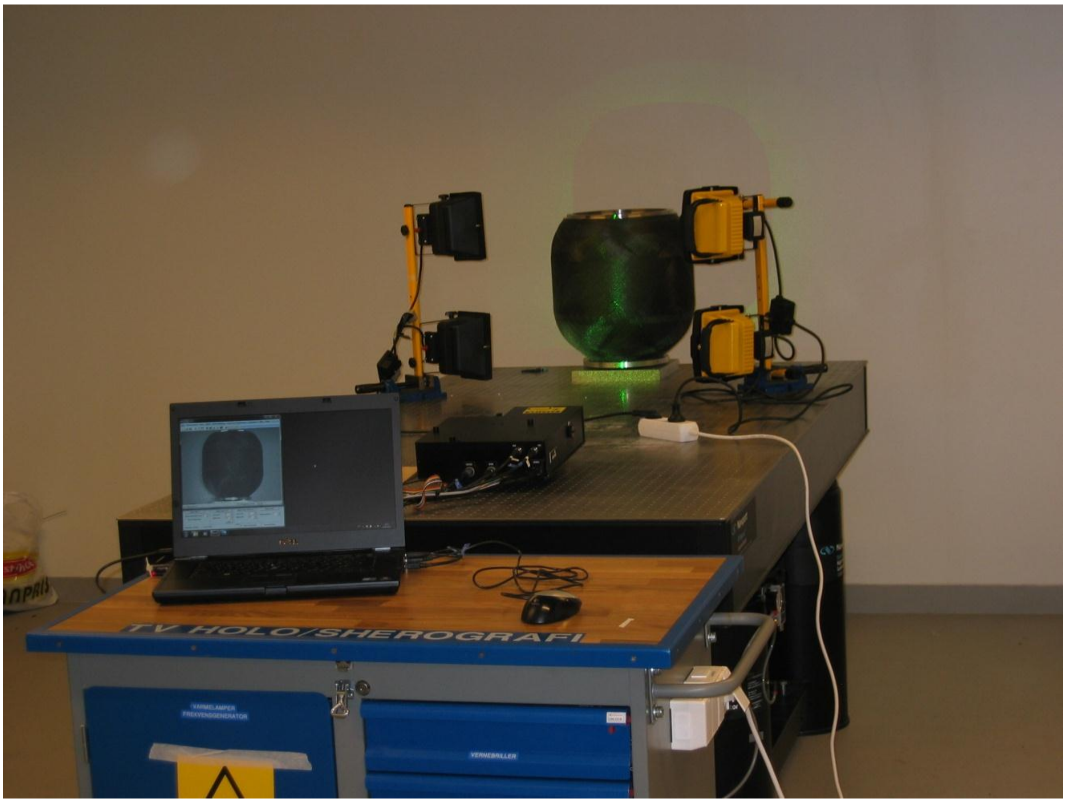

Figure 4.3 TV holography set-up. The composite structure is excited using heat.

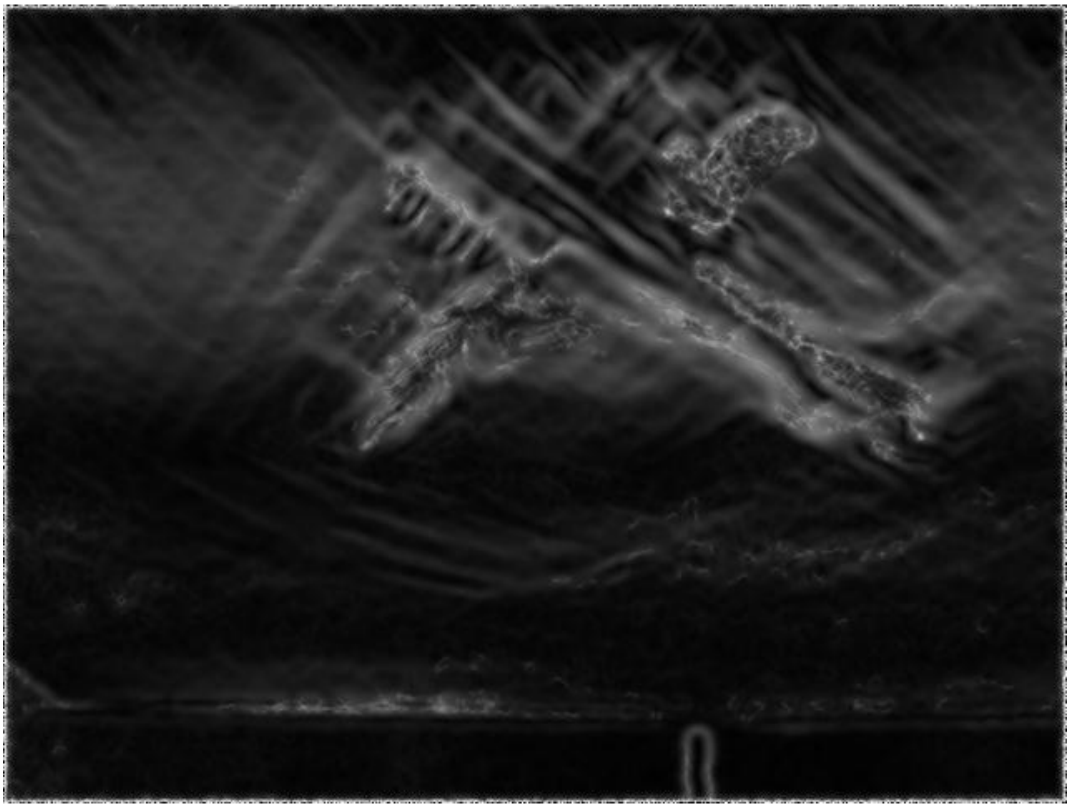

Figure 4.4 TV holography image of a composite shell structure. Defect after dropping of the structure onto a concrete floor from a relatively low height.

An example of a TV holography image of a damaged area is shown in Figure 4.4. In this case, a composite structure has by accident been dropped onto a concrete floor from a relatively low height. There is no visible (for the human eye) defect of the surface, but the structure is in fact seriously damaged, and the strength is reduced considerably.

4.6 Advantages and disadvantages

TV holography is a contactless and sensitive method that makes it possible to examine large surface areas at the same time. Since it does not require any scanning of the surface, TV holography is a quite time efficient method [10].

Even though ESPI, or TV holography, tolerates more excessive displacements than traditional holography, it is still very sensitive. Any movement between the two beams will affect the obtained fringe pattern. According to Cawley [22] and references therein, tolerated object motion under ESPI is about 100 µm. To ensure the quality of the result, a non-vibrating table is often needed [10]. This is perhaps the main disadvantage of TV holography, as this equipment is impractical, or even impossible to use for testing of larger structures and/or for in-service inspections. In addition, due to the use of laser, a separate room must be dedicated to the testing.

As TV holography only detects damages that actually affect the object under stress, only the more serious abnormalities are detected by this method [10]. Even though this property in some situations may be an advantage, the need for inducing stress into the object is generally a drawback of this method.

The interpretation of the fringe pattern obtained by TV holography is often easier to perform than the interpretation of the pattern from digital shearography, described in Section 5. A further comparison between digital shearography and TV holography is found in Section 5.6.

5 Digital shearography

Digital shearography is nowadays often referred to as just *shearography*, as the images are always digitalized. This method is similar to TV holography described in Section 4. It is an optical NDT method that uses laser light to detect defects by altering of the surface topology under stress. The term *laser shearography* is in some cases also used for this method [6]. While TV holography is detecting damages and abnormalities from the displacement, i.e. from the absolute movement of points on the surface of a structure or component, shearography is detecting them by their inducement of elevated strain, i.e. a description of the derivative of the same displacement field [10]. In this way, the procedure is more resistant to vibration and other disturbing movements than TV holography [3].

Note that shearography in some papers is referred to as *Electronic Shear Interferometry* (ESI) [23] and also *Speckle Pattern Shearing Interferometry* [24].

5.1 Description

In the general set-up for digital shearography, a beam of coherent laser light, i.e. light where all the waves have the same phase and frequency [1], is expanded (by a lens) before it is sent to illuminate the object's surface. The diffuse light reflected from this surface is then sent through a shearography camera, which is shearing and recording the received signals [11;22]. A computer processes this information to produce a speckle pattern of the surface of the object. This speckle pattern is random, due to the fact that the object generally has a rough surface. Two speckle patterns are created: one under the unstressed condition, and one when some kind of load is applied. The combination of the two patterns gives a new fringe pattern that describes the first derivative of the displacement.

Possible types of applied load can, independent of the type of shearing device used, be thermal exposure, vacuum, pressure, mechanical vibrations or static loading, i.e. similar to those used in TV holography, see Section 4.2 [6]. The aim should, however, be to maximize the change in the surface, due to elevated stress in the damaged area, so that this can be detectable by the principles of shearography. Hence, the most efficient type of loading will depend on the given situation. According to Diamanti *et al.* [25], vacuum is commonly used as loading for detection of debonds in composite materials. Examples of shearography set-ups using the different stress mechanisms may also be found in the report from the SaNDI project [6], where test cases and images are displayed, together with method requirements, functionality, time and cost information.

The overall set-up for shearography is very similar to TV holography, as shown in Figure 4.3, with the main difference being the unit receiving and processing the data.

5.2 Different set-ups/measuring techniques

The set-up for the shearing of the reflected light varies between the different measuring techniques found in the literature. Several papers describe a set-up that uses a beam splitter and mirrors for obtaining the shear, i.e. the lateral offset, or distance, between the two beams. Two overlapping pictures then give the interferogram. This is referred to as the *modified Michelson set-up*, see e.g. [1;6;11;12;24]. Hung *et al.* [10;26;27], among others, instead use a prism and a polarizer to obtain the same effect as from beam splitting. According to Kim [28], NDT methods using the principle of shearography can generally be divided into these two main groups: 1) methods using a Michelson interferometer, and 2) methods that are using other shearing elements, such as prisms or glass wedges. We will describe them in the following.

5.2.1 Modified Michelson set-up

In the *modified Michelson set-up*, also referred to as an Michelson interferometer [28], the shearing of the reflected light from the surface is done by the use of a beam splitter and two mirrors, see Figure 5.1. The light reflected from a random point on the surface will, when it is sent through the beam splitter, be divided in two new beams, marked as blue and red lines in Figure 5.2. They are referring to the part of the beam that is going straight through the beam splitter, and the other part that is reflected. After this, each of these parts is sent towards one of two mirrors that are reflecting the light towards a CCD camera. The camera is observing and recording the information, which is afterwards processed by a computer, and stored as a speckle pattern of the surface.

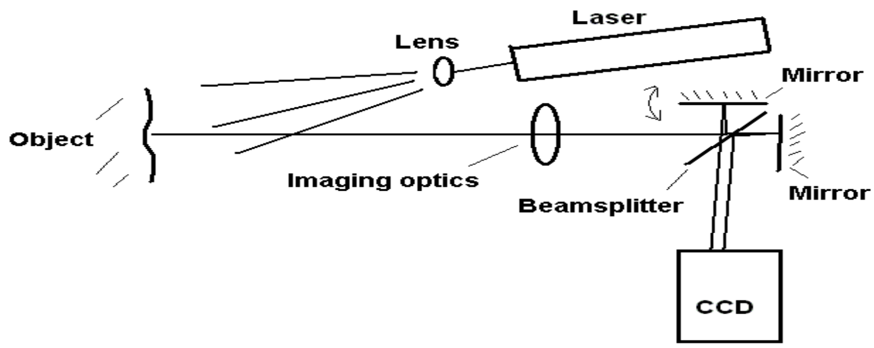

Figure 5.1 Shearography using a modified Michelson set-up. Picture is used with permission from Optonor [1].

In the modified Michelson set-up, one of the mirrors has a small tilt, so the light reflected by this mirror will be laterally displaced on the detector, compared with the other parted beam. Accordingly, the original reflected light beam from one particular point on the surface will be related to two different points on the detector [11], as shown in Figure 5.2. Hence, two laterally sheared images of the surface are observed on the detector [12]. This implies that one point on the detector will receive signals from two neighbouring points of the physical object, as the parted beams from two physical points on the object hit the same location on the detector, due to the lateral shearing by the tilted mirror. In Figure 5.2, this can be seen as the point on the detector where the blue and (one part of) the orange dashed line coincide.

Since two signals reach the processor in the same point, there will be interference between them. It is this interference that is recorded by the detector and used to produce the speckle pattern of the objects surface. As the relative phase between these two interfering signals will change when the surface is deformed, due to applied load on the object, the obtained speckle pattern will change as well [11]. By comparing these two speckle patterns, one from an unstressed state and one from a stressed state, a description of the derivative of the displacement of the surface is obtained. This is expressed as a fringe pattern.

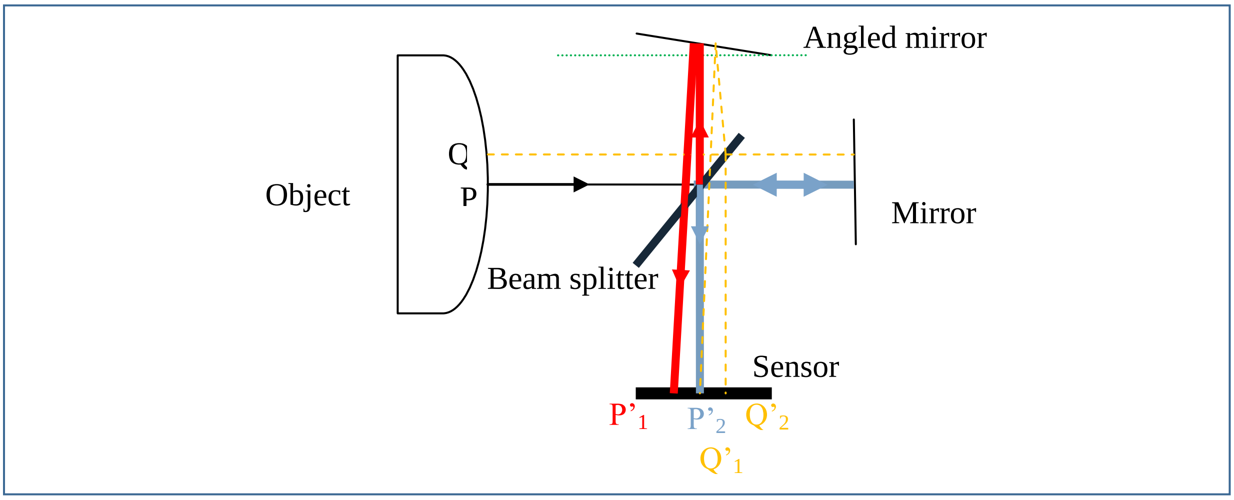

Figure 5.2 Shearography using a modified Michelson set-up. The light reflected from one point, P, on the surface is split in two, shown as blue and red lines. Light from a single point P on the surface is related to two points, P'_1 and P'_2, on the sensor. Due to this property the sensor is observing two laterally sheared images of the surface of the object.
The orange dashed line shows the light reflected from a neighboring point Q. Note that the blue line and one part of the orange dashed line coincide at the same point, i.e. $P'_2 = Q'_1$, on the sensor.
For simplification, the lens between the object and the beam splitter is left out from this sketch.

5.2.2 Prisms as shearing device

As mentioned above, Hung *et al.* [10;26;27] use a special crystal, i.e. a double-refracting prism, in their shearing device. When this prism is receiving two non-parallel beams, which are reflected from two neighbouring points on the surface of the object, it will refract them to be close to collinear [26]. These new, sheared beams are orthogonally polarized, so to obtain interference, a polarization device is needed. After being sent through this polarizer, the interference effect will be observed by the camera, and the information results in a speckle pattern of the surface.

A schematic description of the set-up can be seen in Figure 5.3. The interference is observable by the CCD camera (similar to the Michelson set-up), due to the effect of the shearing device, as this is reducing the spatial frequency of the interference fringes [26]. Also note that the process of bringing the light reflected from two neighbouring points on the object to coincide at one point on the detector of the CCD camera, is equal to letting the light from one point on the object split into two different points on the same detector [10] .

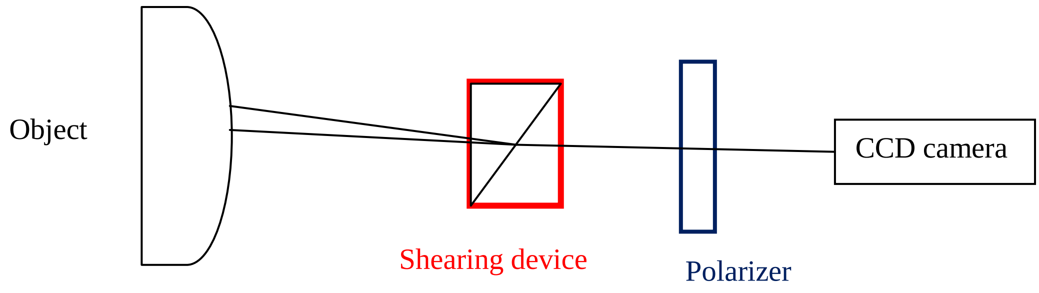

Figure 5.3 Set-up for shearography that uses a double refractive prism as a shearing device.

Hung and Ho [26] on their side prefer using a Wollaston prism as a shearing device, as this prism has a wider viewing field, producing fringes with higher quality, and is more light efficient. However, the phase-shifting technique (see Section 5.3) is easier preformed on set-ups using a Michelson interferometer than on those using a Wollaston prism as the shearing device [28].

Note that the set-ups described above are used for measuring of out-of-plane strains. If instead in-plane strain is to be measured, a different set-up with a dual illumination of the object is needed [27].

5.3 Phase-shifting

Phase-shifting techniques are added to the original set-up of digital shearography[2] to obtain an automated determination of the fringe phases in the output of the test; a manually interpretation of the images is often challenging [28]. An additional phase is added to the speckle pattern multiple times, and this makes it possible to automatically obtain information about the phase-change distribution of the speckle pattern. The determination of this distribution is performed based on the assumption that the random phase of the speckle pattern remains constant during deformation, but that the total phase is altered, due to addition of the phase change [26].

This phase-shifting can be performed in several different ways. It is possible to tilt either the object or the light beam, translating the shearing device to use a variable wave retarder, or to use polarization to manipulate the wave front. The latter is described by Hung and Ho [26], where a prism is used as a shearing device. In the modified Michelson set-up, the phase-shifting technique is being accomplished by letting the non-tilted mirror be assembled to a pizoelectrical

[2] Phase-shifting techniques are also applied in TV holography.

crystal. This is inducing a linear movement on the mirror, and hence adding the desired additional phase [28].

5.4 Optically excited lock-in shearography

Another way of improving the results obtained form shearography is to make use of the lock-in principle. In *optically excited lock-in shearography*, modulated heat is induced onto the object by letting a lamp with modulated intensity illuminate the surface [11]. This will lead to a periodically change of the surface temperature of the object, followed by a thermal wave of heat transmitted through it. As this wave will be reflected by internal defects in the material, the deformation state of the surface of the object will be altered.

During this periodically excitement of the object, a speckle pattern of the surface is continuously recorded. By adding a temporal phase-shift, and then performing a comprehensive analysis of the images, a thermal lock-in phase image, that is displaying the local delay in thermal phase between the excitement and the response, is obtained. This image combines the information from a complete series of recorded pictures, and the phase information is used to detect damages.

5.5 Types of damages and materials

Damages are detected by shearography if they lead to elevated strain on the surface when the object is exposed to stress. The areas with elevated strain levels can be recognized as abnormalities in the fringe pattern. For example, debonds will be displayed as butterfly-like shapes [26]. The outer size of the butterfly describes the actual size of the debond, while the number of fringes is correlated to how deep in the structure the defect lies. The closer the defect is to the surface, the more fringes will be observed. Actually, the density of the fringes is inversely proportional to the cube of the depth of the defect, given that the debonds have equal size [26].

Since most damages, unless they are located very deep in the structure, will affect the strain on the surface, damages in both the surface and more deeper structures can be detected with shearography [27]. In composite laminates, debonds are detectable by shearography with good security [26]. This method can also be applied for detecting delamination and edge pullout [10].

5.6 Advantages and disadvantages

One advantage related to shearography, is that it is contactless. Moreover, it is possible to examine large areas at the same time. Hence, no scanning of the surface is needed, as is the case for, among others, coin tapping and ultrasound methods. The restrictions on the size of the (simultaneously) examined area lies on the intensity and broadness of the laser beam [3], as well as the size of the viewing field of the shearing device. A general disadvantage of this method is that the object actually needs to be in a loaded state. This is not required when using, for example, ultrasonic methods.

Furthermore, shearography (and TV holography) are only able to detect damages that actually changes the strain of the surface of the object [10]. For example, since there is no obvious correlation between porosity and measurable surface deformation, this type of damage can be difficult to detect [29].

The shearography method also needs visual access to the surface of the object, and sufficient space in front of the object to set up the equipment. To reduce the demand on the required area in front of the surface, Schuth *et al.* [24] took advantage of the features of endoscopy. More detailed description of this technology can be found in their paper and the references therein.

For translucent and mirror-like surfaces, it might be necessary to paint the surface to reduce the direct reflex, since this will create weaker fringes on the pattern, due to elevated light reflection [6]. However, according to Zhang *et al.* [30], during the past few years this problem has been greatly reduced due to some general improvements, such as reducing the distance between the laser and the camera, and raising the signal-to-noise ratio (SNR) of the system.

Shearography is insensitive to abnormalities that is positioned at different depths in the material [11]. Also, the normal deformation of the object under stress can hide the effect of the defects.

When comparing shearography and TV holography, shearography has a simpler set-up, because it is detecting the derivative of the displacement, and hence it does not require a reference beam. Accordingly, it has neither the same demand for a long coherent laser or a vibration isolated table [27]. The degree of tolerated movement in the shearography method is still strictly limited, although the limit is higher than for TV holography [26]. In addition, shearography has the advantage over TV holography that it directly measures the strain of the surface [10]. TV holography, on the other side, is more sensitive to small alterations than shearography [10]. This may in some situations be a disadvantage of TV holography, as the sensitivity is higher than what is practical for non-destructive testing.

6 Summary

In this report, three non-destructive inspection methods for analysis of composite materials have been discussed. The methods have been briefly described, types of damages detectable by the methods have been discussed, and advantages and disadvantages have been listed. A comparison between the methods has also been included. The main focus has been on composite materials. A summary of the methods, as well as their applicability to detect various damages for composite materials, is shown in Table 6.1.

Note that it is not intended in this survey to cover all aspects of the methods or all techniques available. Still, the report should give a relatively good introduction to the methods described.

Table 6.1 Summary of the different NDT methods and their applicability to different composite materials.

Method	Section	Possible to detect	Examples	Difficult to detect
Manuel coin tapping	3.1	Damages that alters the object's sound response	- delamination of face laminate - skin-core debonding	- deep damages - porosity - fibre breakage
Force-time analysis	3.2	Damages that changes the object's stiffness	- delamination - debonds	- deep damages - fibre breakage - fibre misalignment
Mechanical impedance	3.3	Damages that lead to separation between the materials of the composite, resulting in changes in the object's stiffness	- delamination in laminates - skin-core debonding - debonds in adhesive joints - local contact damage in sandwich structures	- transverse cracks - deep damages in the core of sandwiches or close to the back wall
TV holography	4	Damages that deforms the surface of the object, when loaded	- debonds close to the surface - delaminations in sandwiches	- porosity - deep damages
Digital shearography	5	Damages that deforms the surface of the object, when loaded	- debonds close to the surface - delaminations in sandwiches	- porosity - deep damages

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Appendix A Additional sources

A.1 Links

The following list provides some relevant links to sites discussing/describing non-destructive testing methods:

- http://www.rnde.org/
- http://www.asnt.org/
- http://www.ndt-ed.org
- http://www.netcomposites.com

A.2 Conferences

- www.etech-ndt5.uoi.gr
- http://www.ndt.net

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