Application of Shearography Techniques for Vibration Characterization and Damage Detection in Sandwich Structures

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SUMMARY

The paper presents a new Electronic Shearography (ES) system for Structural Health Monitoring and damage detection, where a huge step in sensitivity has been accomplished compared to earlier shearography systems. Debondings and delaminations in sandwich panels can be detected from a distance of several meters. We are able to detect changes in the surface of a few nanometers even in noisy enviroments. The test setup and measurement routine are fast and easy. Todays technology demonstrator covers test-areas from sqcm to about 0,5sqm but with further development larger test areas can be achieved. The measurements can be done by static loading or by dynamic excitation. By static loading one measures deformations in the surface after loading by heat or pressure. The dynamic excitation is done by vibrating the test object and record the vibration pattern. When a damaged area is loaded statically, or excited dynamically it may react differently than undamaged areas, the damage detection is based on finding something that "stands out" from the rest of the measurement. It is usually easy to see the damage even for the untrained eye. The system is also ideal for difficult geometries such as corners and curved objects because of the easy excitation and measurement method.

Examples from both static and vibrational measurements on composite materials are included in the paper. The tests are done with a technology demonstrator developed by Optonor AS [1].

1.0 INTRODUCTION

In recent years sandwich materials have gained increased use as a ship construction material, especially in naval vessels. The work reported on Electronic Shearography (ES) in this paper was started as a part of the international research project NATO WEAG JP3.23 "Inspection and Repair of Sandwich Structures in Naval Ships" [2]. Special emphasis has been on structural health monitoring (SHM) and damage detection on the sandwich panels used in the Norwegian Navy Oksoey, Alta Class Mine Counter Measure Vessels and Skjold Class Fast Patrol Boat. An example of a Fast Patrol Boat is shown in Figure 1. Today the vessels are inspected by manual cointapping, which is very time consuming when inspecting larger part of the vessel. With the new ES system large areas can be tested for damages fast and safe.

Wivesoll Vollen, M.; Vikhagen, E.; Wang, G.; Egil Jensen, A.; Jarle Haugland, S. (2005) Application of Shearography Techniques for Vibration Characterization and Damage Detection in Sandwich Structures. In *Recent Developments in Non-Intrusive Measurement Technology for Military Application on Model- and Full-Scale Vehicles* (pp. 21-1 – 21-14). Meeting Proceedings RTO-MP-AVT-124, Paper 21. Neuilly-sur-Seine, France: RTO. Available from: http://www.rto.nato.int/abstracts.asp.

Figure 1: Royal Norwegian Navy's Fast Patrol Boat KNM Skjold on duty in the North Sea.

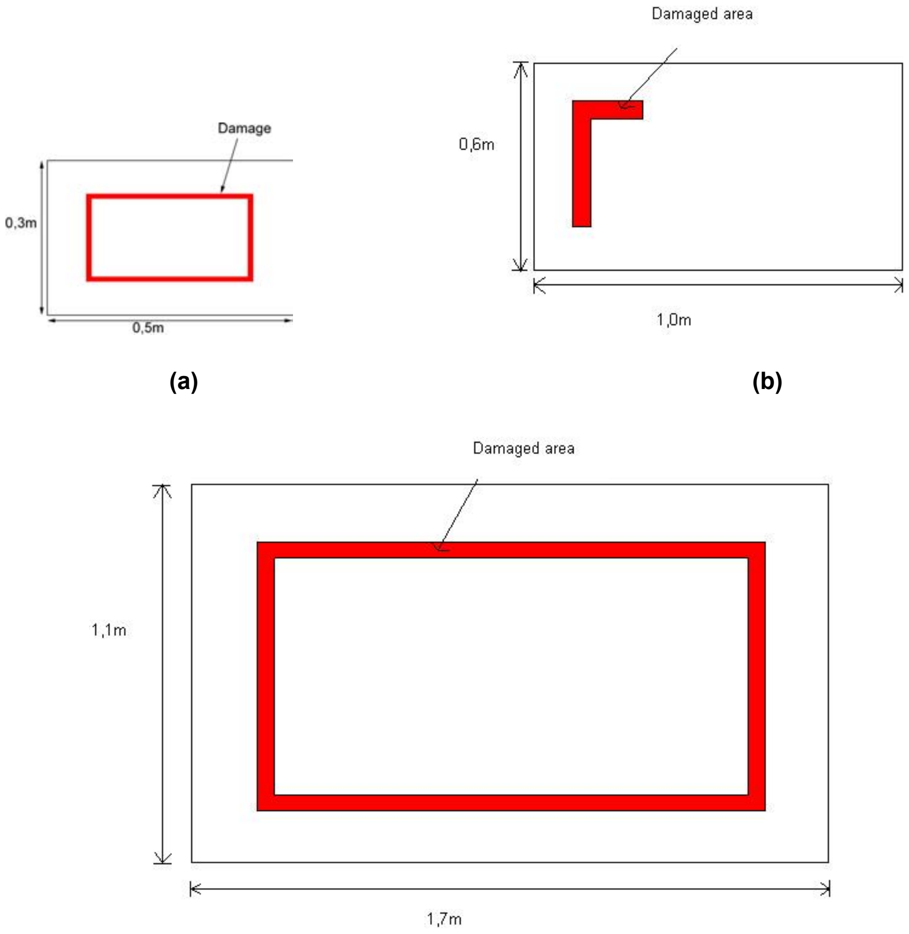
When an object under investigation is excited dynamically or loaded statically or thermally, the object surface displacements may reveal the existence of surface or sub-surface defects, since these defects may influence on the surface displacements. Typical defects that can be detected in sandwich panels are debondings and delaminations, core failures, impact damages and surface cracks.

Some shearography systems use vacuum to reveal defects and damages. Because of the need for a vacuum camber, this particular method is not very flexible and fast. The vacuum technique is also very difficult to apply on complex geometries like curved and double-curved areas, and at corners. We introduce a new system that is more sensitive than traditional systems and can be used in noisy environment.

In Chapter 2.0 a general description of sandwich panels is given, where the test panels used for this paper is sketched with damages. Chapter 3.0 explains the basic principle of ES, and the new features with this system, the phase gradients calculations and the vibration animations. Examples of measurements on the test panels are given.

2.0 SANDWICH PANELS

Several tests have been performed to validate the systems ability to detect damages in sandwich panels. A sandwich material combines high strength and stiffness with low weight [3]. This is obtained by using a soft core material in the middle covered with relatively thin upper and lower skins, hence the name sandwich. With new materials, new damages occur and one needs damage detection systems to detect these damages and weaknesses before they become fatal. A naval twin-hull vessel is exposed to waves slamming into the wet deck (the deck connecting the two twin hulls of a catamaran), and gun blasts. This is causing overload in the panel's surface pressure and damages may occur. A typical damage in a polymer based sandwich material is a separation of the core and skin, a so-called debonding. This leads to a reduction in stiffness for the damaged panel. The test results included in this paper is of damages that typically occur when waves slam into the wet deck of a vessel at sea. Three different sandwich panels with damages as shown in Figure 2 were used for the tests. Figure 3 shows an example of damage, shear crack with subsequent debonding.



(a) **(b)**

(c)

Figure 2: Test panels with damaged area marked in red, (a) panel 1 has a core shear failure (45 degrees) along all edges, (b) panel 2 has a pure debonding damage, and (b) panel 3 has a shear crack across the core with subsequent debonding as seen in Figure 3.

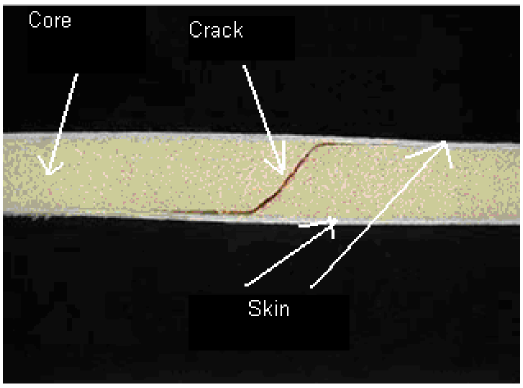
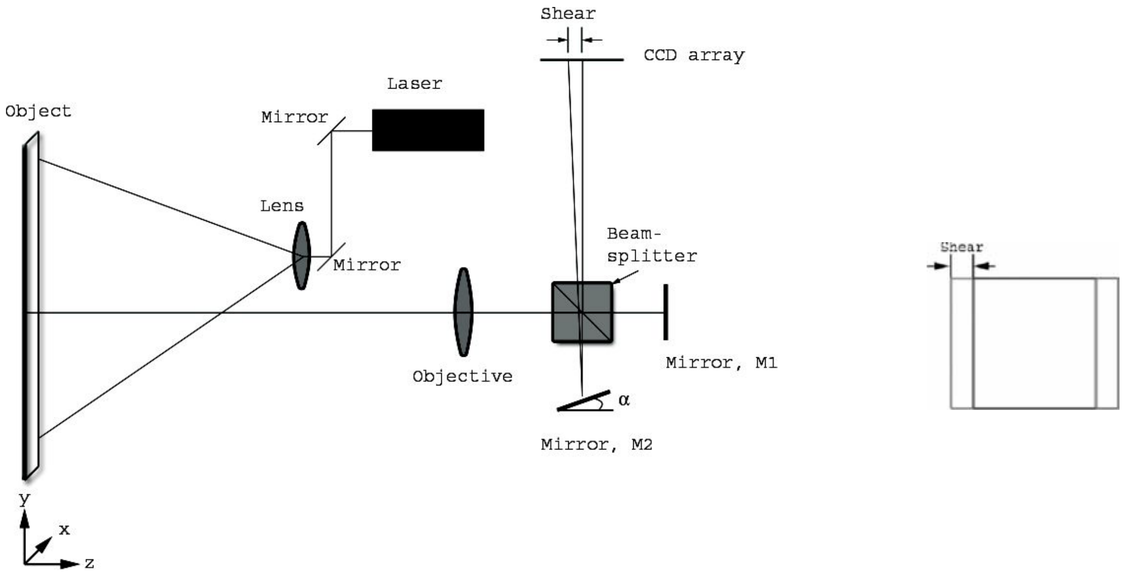


Figure 3: Shear-induced cracking of the core and subsequent debonding.

2.0 THEORY/PRINCIPLE



(a) **(b)**

Figure 4: (a) The test area is illuminated by a coherent light source. A light wave reflected from the test area is passing through a modified Michelson interferometer, where one of the mirrors has a small tilt. This means that a light wave from one point at the test object ends at two points at the detector. The distance between the two points at the detector is called shear. The shear size can be changed by changing the angle of one of the mirrors. By shifting one of the mirrors a controlled uniform phase can be added to one of the two interfering waves. (b) Two images of the test area are imaged on the detector, the lateral displacement between the two images is called shear.

A shearography image can be related to the gradient of a deformation or vibration. The basic principle is that the test area is illuminated by one or more coherent light sources, lasers, and imaged on to a detector, Figure 4a. On the detector two images of the test area are imaged with a small lateral displacement with respect to each other, Figure 2b. The lateral displacement is called shear. This means that light reflected from two neighbouring points at the test object interferes at the detector. Hence the displacement of each point on the object surface is measured relatively to a neighbouring point on the surface. The intensity distribution on the detector, $I(x,y)$, can be described by

$$I(x,y) = I_b(x,y) + I_m(x,y)\cos(\alpha(x,y) + \phi)$$

Where $I_b(x,y)$ is the background intensity (the average intensity of the two sheared light waves), $I_m(x,y)$ is the modulation intensity, $\alpha(x,y)$, is the initial phase difference between the two light waves, and ϕ is a controllable uniform phase shift controlled by shifting one of the mirrors.

Similar techniques described in this paper have earlier been developed for Electronic Speckle Pattern Interferometry (ESPI) systems. ESPI and ES have many similarities when they are both based on interferometry, and have the same basic sensitivity, since the wavelength of light is the basic measurement unit for both techniques. The difference between ESPI and ES is that with ESPI a smooth reference beam is interfering with the object light wave, while with ES the two waves interfering are both reflected from the test object. Hence, with ESPI, the displacement of each point on the object surface is measured relatively to the optical head (absolute displacement), whilst with ES, the displacement of each point on the object surface is measured relatively to a neighbouring point on the surface (the spatial derivative of the object surface displacement). This gives ES advantages in field applications. Because ES measure the spatial derivative instead of the absolute displacement, pure piston movements of the test object are not recorded. This makes it relative insensitivity to environmental disturbances. And ES has in general larger measurement range than ESPI, with ES the measurement range can be controlled by adjusting the shear size.

2.1 Static Loading and Phase Calculation

The static measurements are based on comparing two states of the object being tested, one before and one after loading by pressure, heat, etc. A series of images are recorded and digitalized of the test object in both conditions. The intensity distribution on the detector after loading can be described as

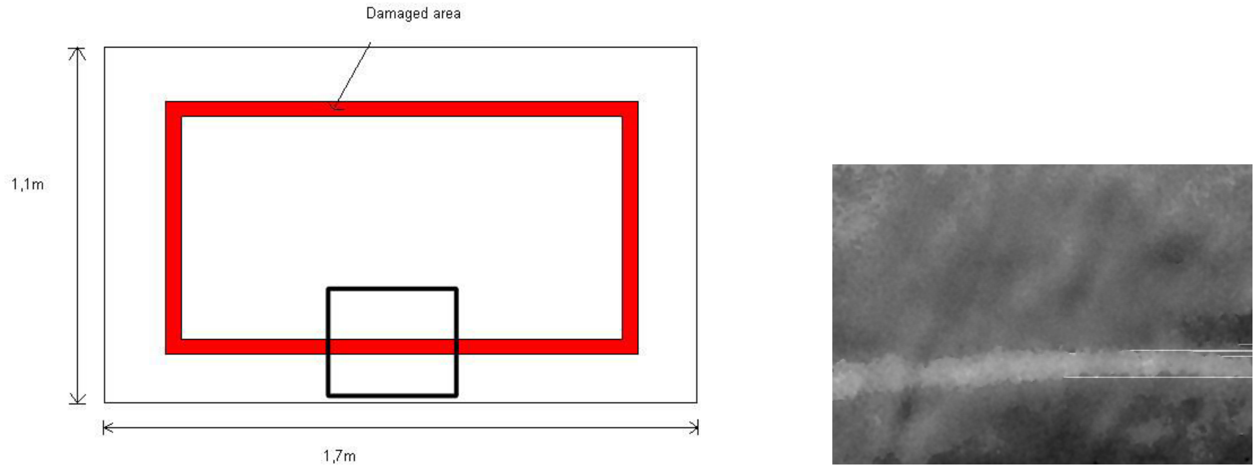
$$I(x,y) = I_b(x,y) + I_m(x,y)\cos(\alpha(x,y) + \beta(x,y) + \phi)$$

Where the phase $\beta(x,y)$ is given by the object's displacement, and is the value we want to look at. By traditional phase shifting the phase value $\alpha(x,y)$ before loading and $\alpha(x,y)+\beta(x,y)$ after loading can be found. The controlled phase, ϕ, is set to 0, $\pi/2$, π and $3\pi/2$, and for each ϕ an image is recorded creating a total of four images $I_1(x,y)$-$I_4(x,y)$ before loading and four images after loading.

$$\alpha(x,y) = \arctan\left[\left|\frac{I_4(x,y) - I_2(x,y)}{I_1(x,y) - I_3(x,y)}\right|_{unloaded}\right]$$

$$\alpha(x,y) + \beta(x,y) = \arctan\left[\left|\frac{I_4(x,y) - I_2(x,y)}{I_1(x,y) - I_3(x,y)}\right|_{loaded}\right]$$

The sign of the phase $\alpha(x,y)$ is given by the sign of the numerator and the denominator [4]. By simple subtraction the phase change due to the loading, $\beta(x,y)$, can now be found. In Figure 5 a sandwich panel has been loaded by heating and the phase change has been calculated. In addition the phase change, $\beta(x,y)$, has been unwrapped for a more easily evaluation of the image [5].



(a) (b)

Figure 5: Measurement from panel 3, static loading by heating the test area from the front (a) The black square indicates the measurement area, (b) the phase change, β(x,y), the light coloured area is the damaged area.

2.1.1 Phase Gradient

A more robust use of the phase information has been developed, so called phase gradient calculation. This technique has earlier been used in ESPI [6]. The procedure is just sketched in this paper, for a more thoroughly explanation the articles earlier written on the use of this in ESPI will be useful. First the phase change, *β(x,y),* is calculated as explained above. Then the gradients in two orthogonal directions are calculated

$$\left[\frac{\partial\beta(x,y)}{\partial x}\right] = \left|\beta(x,y) - \beta(x-1,y)\right|$$

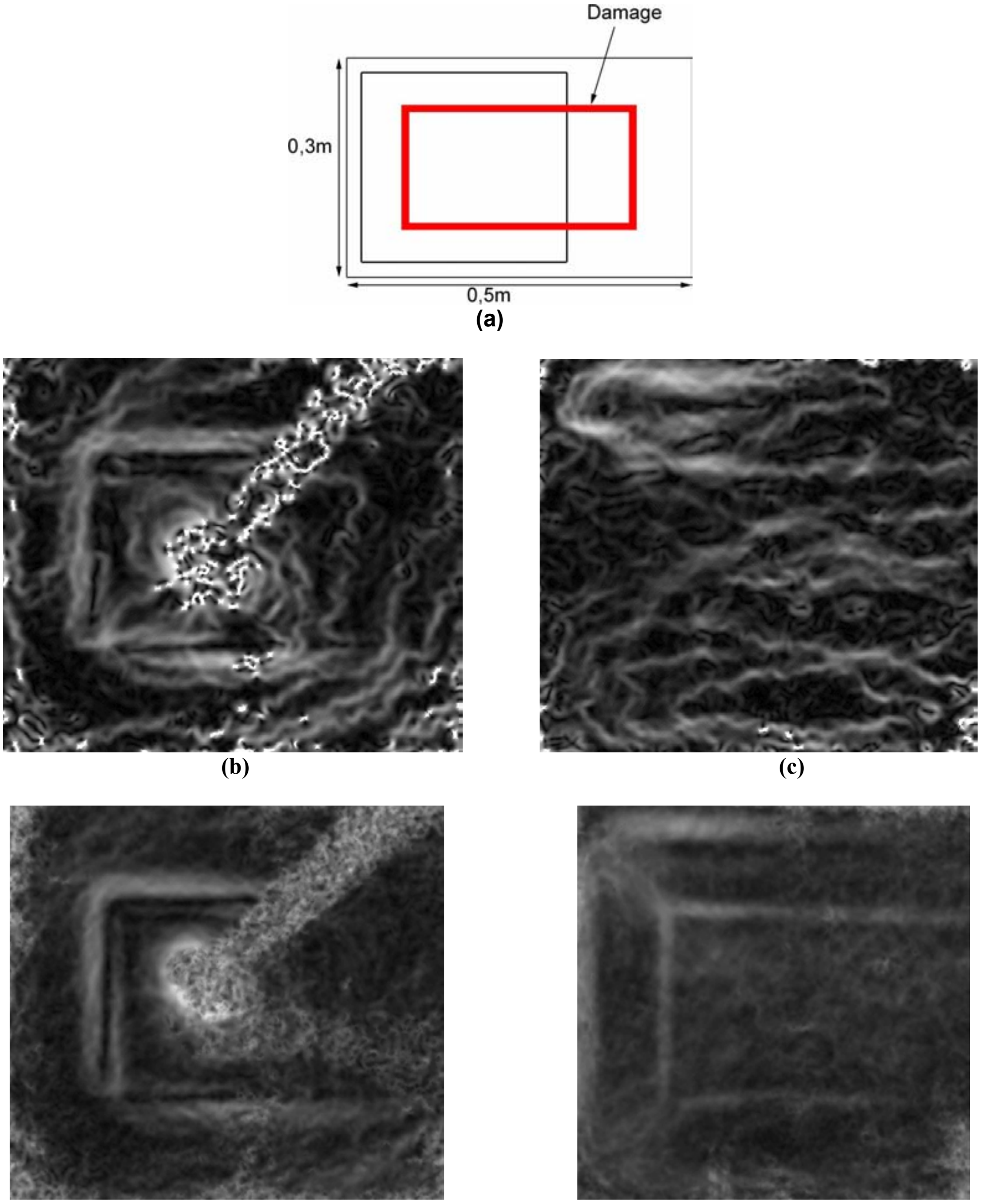
$$\left[\frac{\partial\beta(x,y)}{\partial y}\right] = \left|\beta(x,y) - \beta(x,y-1)\right|$$

Discontinuities that occur are eliminated as explained in [6].

The total phase gradient is then given by

$$\left[\frac{\partial\beta(x,y)}{\partial s}\right] = \sqrt{\left[\frac{\partial\beta(x,y)}{\partial x}\right]^2 + \left[\frac{\partial\beta(x,y)}{\partial y}\right]^2}$$

This value is now smoothed, and speckle averaging is performed. Speckle averaging is done by averaging over several decorrelated speckle patterns. This increases the resolution substantially as seen in Figure 6.



(a)

(b)

(c)

(d)

(e)

Figure 6: Measurement from panel 1, phase gradient measurement, (a) the black square indicates the measurement area, on the left side the loading is done by pressure (broom stick), and on the right side loading is done by heating from the back, (b) and (c) have no speckle averaging, (d) and (e) have 16 speckle averaging.

2.2 Vibration Analysis

The basic principle of the new system for damage detection is as follows: The panel is excited dynamically in a point by a shaker either from the front or the back as seen in Figure 7 and the vibration pattern is recorded. Then an animation of the vibration is created. Both the natural frequencies of the test object and other vibrations like surface waves can be recorded. The damage is found as anomalies in the vibration pattern.

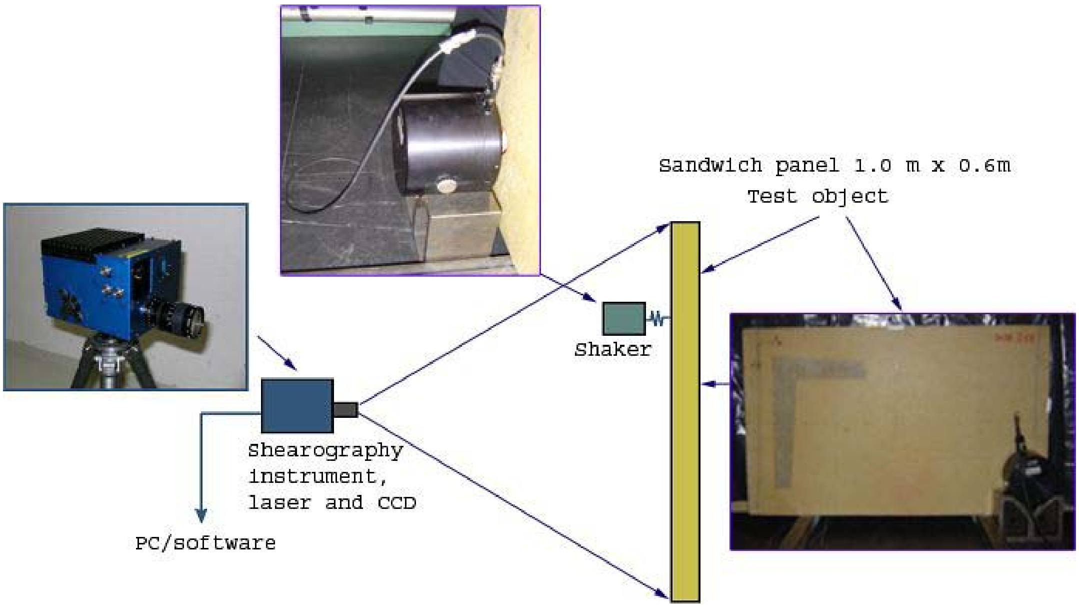


Figure 7: The test panel is illuminated by coherent light and excited in a point by a shaker either from the front or the back, so that the test face is vibrating with a fixed frequency and amplitudes approximately 10-50 nm.

The recording technique is based on time average recordings, meaning that the vibration frequency is much larger than the frame rate of the camera, or with other words; the exposure period is much larger than the vibration period. The detector does not resolve (in time) the fast modulation of the surface displacements. The direct image on the camera can be described by a Besselfunction, where iso-amplitude fringes are seen [7].

The testobject is excited with one frequency at the time (100Hz – 10kHz), and by means of a lock-in technique that controls object vibration, one can calculate the vibration peak-to-peak amplitude distribution and vibration phase distribution over the object surface. This is a similar technique earlier used for ESPI. Based on the phase- and amplitude distribution animations of the propagating waves can be created from the equation

$$A(x,y) = A_0(x,y)\sin(P_0(x,y) - T)$$

where $A_0(x,y)$ is the amplitude distribution, $P_0(x,y)$ is the phase distribution, and T= ωt is a phase with value between (0-2π). By altering the phase T systematically between 0 and 2π one can develop an animation of the deflection gradient. Each picture will then represent the deflection gradient at a given time, t. The animation of the vibration pattern will be shown in slow motion. While conventional shearography only detects resonance frequencies this system will show the overall vibration pattern, both travelling wave and standing wave, and damages not detectable by conventional shearography can be detected.

The lock-in technique filters away noise and frequencies other than the applied frequency. This gives us increased sensitivity. In addition a speckle averaging technique is used for removing speckle noise.

For an infinitely large undamaged panel the vibration pattern would look like rings in water, travelling waves that spread out from the excitation point as shown in Figure 8. But for a finite panel like the test panels one will get reflections from the end faces and from the stiffening and combinations of travelling and standing wave occur. In the damaged areas the waves will change properties compared to the waves on the rest of the panel, such as higher amplitude, shorter wavelength etc.

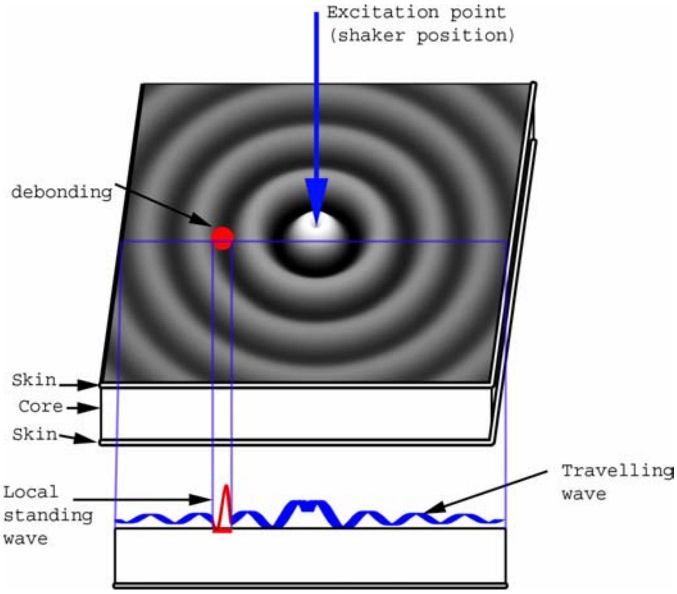


Figure 8: A damage will appear as an anomaly in the overall vibration pattern.

In Figure 9 test result from sandwich panel with a pure debonding damage is shown.

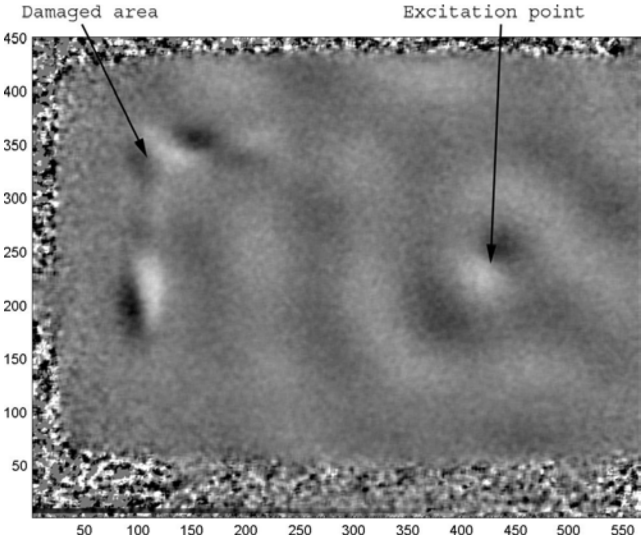
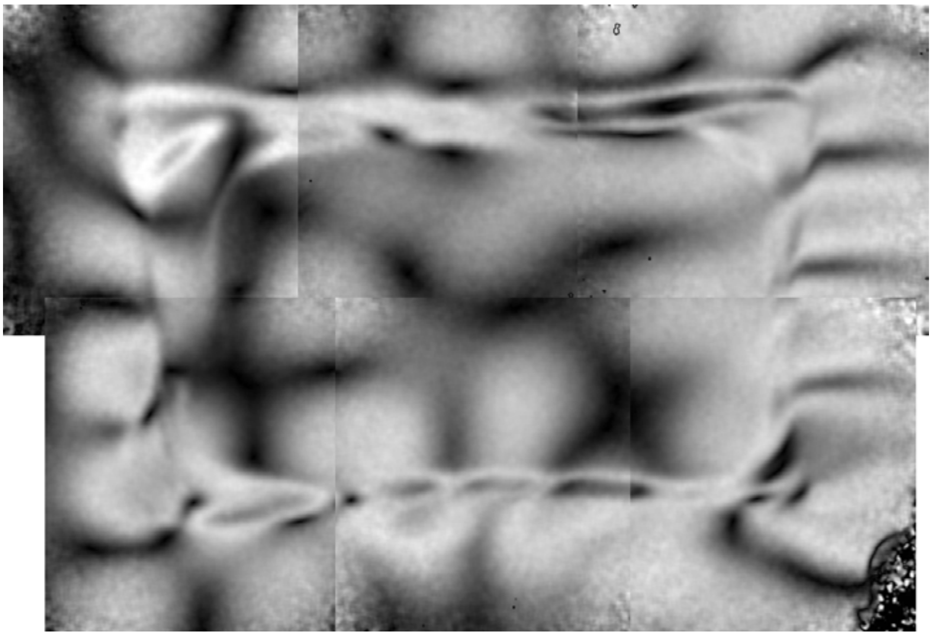
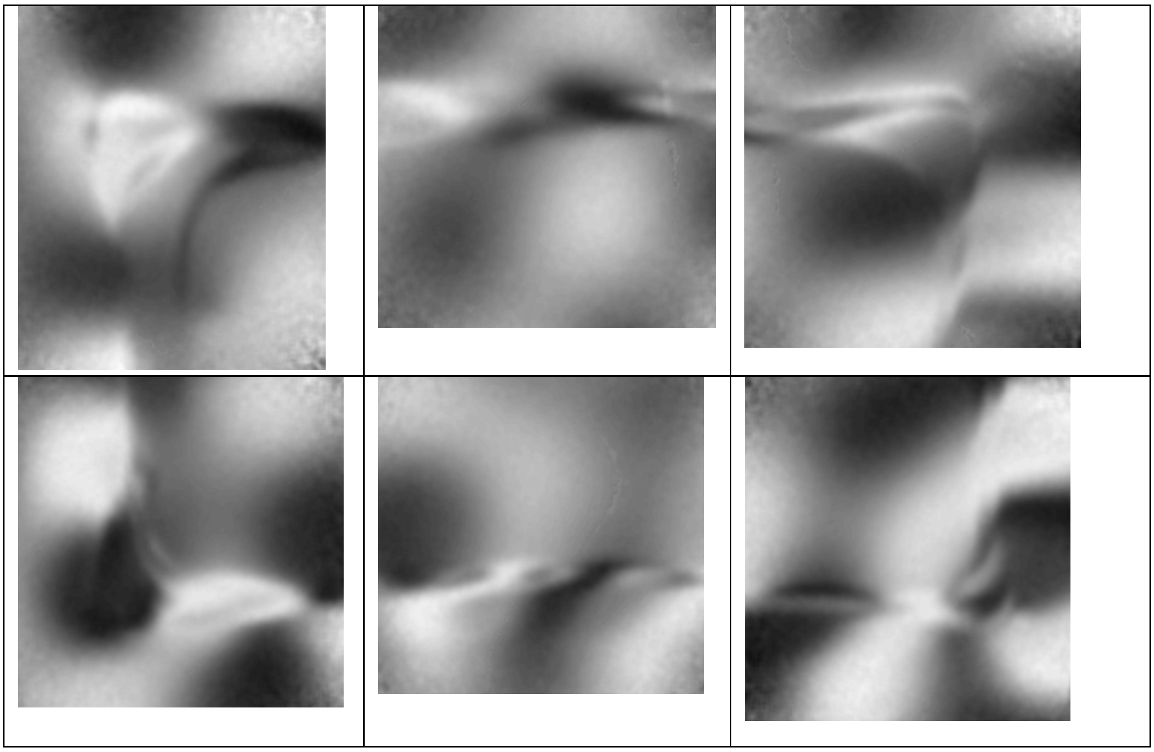


Figure 9: Panel 2 is excited with frequency 1,7kHz from the back.
The damages are found as anomalies in the overall vibration pattern.

In Figure 10-11 the results from tests on a larger sandwich panel is shown. The panel was too large to take in one recording so the amplitude images are put together to form a total image of the vibration pattern. The excitation frequency is 1 kHz for both measurements, but the shear direction is in two orthogonal directions. Sometimes damages that run along the same direction as the shear can be hard to discover.

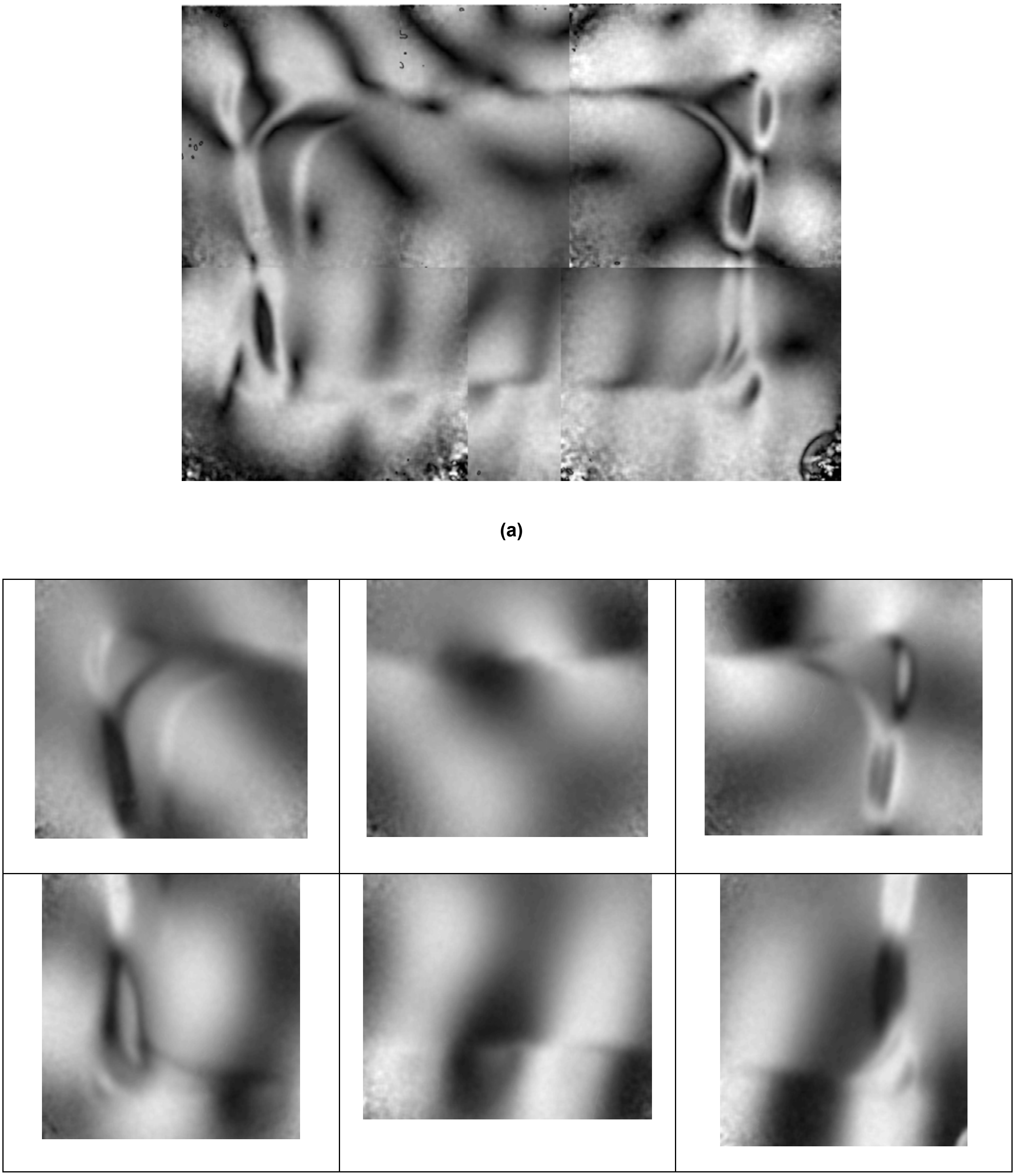


(a)



(b)

Figure 10: Panel 3 is excited with frequency 1kHz and the measurements are done with vertical shear direction, (a) the amplitude distribution, A0(x,y), of the vibration, the shaker can be seen in the lower right part of the picture, (b) the deflection for a given time, A(x,y,t).



(a)

(b)

Figure 10: Panel 3 is excited with frequency 1kHz and the measurements are done with horizontal shear direction, (a) the amplitude distribution, A0(x,y), of the vibration, the shaker can be seen in the lower right part of the picture, (b) the deflection for a given time, A(x,y,t).

4.0 CONCLUSION

The presented work shows very promising results on damage inspection of large-scale sandwich structures with ES. Both static loading and dynamic excitation reveals debondings and shear core cracks. The results show successful damage detection by heating form the front or the back of the test area, loading by pressure, or by dynamic excitation. The measurements are done fast and easy, which makes the system costeffective compared to the manual cointapping used today. The measurements can be done contact less and from a long distance. The system is ideal for difficult geometries such as corners and curved objects, and the results are easily documented. But further development work is necessary in order to cover a larger test area, for instance 4 sqm. This can be obtained by using a more powerful laser and improve the design of the interferometer optics and the detector.

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[6] Vikhagen, E., "Nondestructive testing by use of TV holography and deformation phase gradient calculation", Appl. Opt. 29 (1990) 137-144.

[7] Mohan, N., Saldner, H and Molin, N., "Electronic shearography applied to static and vibrating objects", Optics Communications 108 (1994) 197-202.

SYMPOSIA DISCUSSION

Paper 21 "Application of Shearography Techniques for Vibration Characterization and Damage Detection in Sandwich Structures" presented by Marianne VOLLEN

1. Discussor's name: E. SCHWEICHER

Q. (1) First set-up seems to be a modified Michelson interferometer.

(2) You never define what you mean by nanowave. Is it the wavelength or the amplitude?

R. (1) Yes, our system is based on a modified Michelson interferometer where one of the mirror's is tilted to obtain the shearing distance between the two images of the object on the detector.

(2) By nanowave, we mean that the amplitude of the waves applied are on a nanoscale. The wavelength is usually of the size of some cm up to half a meter.

2. Discussor's name: H. ROSEMANN

Q. How sensitive is your system to vibrations?

R. The lock-on and averaging techniques for the vibration system removes (filters away) much of the noise and vibration frequencies other than the applied frequency present.

We have tried the system in a large shipyard with people working all around us and the floor vibrating, and it worked OK. But for more excitation limits, the system needs to be tested further.