Comparison between temporal and spatial phase unwrapping for damage detection using shearography

A. V. Fantin[a], A. Dal Pont[b], D. P. Willemann*[b], A. Albertazzi[a]
[a]Federal University of Santa Catarina, Caixa Postal 5053, Florianópolis, SC, Brasil 88040-970;
[b]Photonita, SC 401 km 1, ParTec Alfa, Celta sl. 313, Florianópolis, SC, Brasil 88030-000

ABSTRACT

Shearography is an optical and nondestructive technique that has been largely used for damage detection in layered composite materials where delaminations and debondings are the most common flaws. In Shearography the sample under test is illuminated using a laser and imaged on a CCD camera. A special optical shearing element allows a coherent superposition of two laterally displaced images of the surface of the sample on the CCD plane. The images are recorded for different loading conditions of the sample. The loading should induce some deformation or alter the deformation state of the surface of the sample. In this work a thermal loading has been used. The absolute difference of two phase maps recorded at different loading situations of the sample results in an interference fringe pattern which is directly correlated to the difference in deformation state. The phase maps usually have strong noise and low contrast. For this reason, a further improvement in image quality should be obtained. Two methods, known as "difference of phases" and "phase of differences", are used with a spatial and temporal phase unwrapping algorithms, respectively, in an experiment using a steel pipe wrapped in a composite sleeve. A qualitative comparison of the methods is done and the results, advantages and difficulties are discussed.

Keywords: shearography, temporal phase unwrapping, composite materials, optical interferometry.

1. INTRODUCTION

The expanding use of composite materials in modern mechanical systems requires, nowadays, the application of non-destructive testing (NDT) techniques that can reliably monitor the damage state of these composite material structures. Since composite materials are non-homogeneous and present low energy absorption coefficient, they have frequently, in their interior, defects that decrease their mechanical performance. These defects can be caused due to impact loads, like tool drops during maintenance, bird strikes or impacts with other projectiles during service, in the case of airplanes, or even in the application of layers of composites on gas extraction pipes aiming anti-corrosion protection or structural reinforcements [1]. That is why, the demand of safety in the composites field is increasing always more. In this sense, safety means improvements in the composite materials characteristics and in their manufacturing process and also periodic inspection on the structures which can easily be done by means of non-destructive techniques.

At the moment, there are many NDT techniques available, but only a few allow in situ analysis. The requirements for non-destructive evaluation methods are continuing to be driven by the need for lower cost methods and instruments with greater reliability, sensitivity, user friendliness, high operational speed (online inspection), applicability to increasingly complex materials and structures, full-field and non-contact features [2].

Important results have been achieved in the field of non-contact sensors by using electro-optic methodologies and, in particular, those based on laser techniques. Among the different laser-based techniques for non-destructive testing, shearography is one of the most investigated and used, mainly because of its flexibility and applicability in a wide range of testing situations and also due to relative insensitivity to environmental disturbances [3]. For instance, the rubber industry routinely uses shearography for evaluating tires. Other applications for shearography include: measurement of strains, material properties, residual stresses and others [4].

In fact, non-intrusivity is a fundamental feature of the shearography technique. In certain situations, where non-contact is required, the conventional transducers, based on the use of strains gages become difficult to be employed and always involve complex and costly installations. Furthermore, if a high number of measurements have to be taken on different

Seventh International Conference on Vibration Measurements by Laser Techniques: Advances and Applications, edited by Enrico Primo Tomasini, Proc. of SPIE Vol. 6345, 634510, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.693149

points, it would be necessary to arrange lots of contact transducers, which is really time-consuming and with lower spatial resolution. Shearography is really advantageous in these situations.

In Shearography the sample under test is illuminated using a laser and imaged on a CCD camera. A special optical shearing element allows a coherent superposition of two laterally displaced images of the surface of the sample on the CCD plane. The images are recorded for different loading conditions of the sample. The loading should induce some deformation or alter the deformation state of the surface. The absolute difference of two phase maps recorded at different loading situations of the sample results in an interference fringe pattern which is directly correlated to the difference in deformation state.

This work presents two different methods to reconstruct the phase map obtained from a measurement to damage detection on a gas extraction pipe using shearography. Thermal loading has been used during the measurement process. The phase map usually presents strong noise and low contrast. For this reason, a further improvement in image quality should be obtained with phase shift techniques and phase unwrapping algorithms. Two methods, known as "difference of phases" and "phase of differences", are used with a spatial and temporal phase unwrapping algorithms, respectively, as shown in Figure 1. An experiment using a steel pipe wrapped in a composite sleeve is done to a qualitative comparison of the methods. The results, advantages and difficulties are discussed.

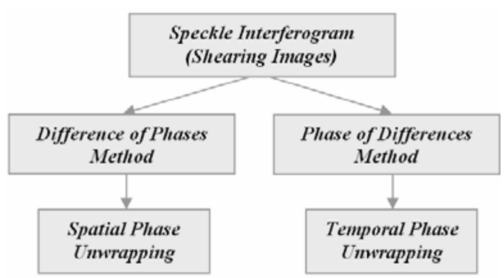


Fig. 1. Different methods to analysis of speckle interferogram

2. SHEAROGRAPHY TECHNIQUE AND MEASUREMENT SETUP

Digital Shearography is an optical measurement technique useful to measure the gradient of the deformation, not the deformation itself, on surfaces. Consequently, shearography measures strain deformation directly. That is why shearography is becoming increasingly important as a measuring tool in industry [3]. In order to perform the measurements, shearography needs three basic elements: an illumination system, an interferometer and software which drives the acquisition of the images. These three elements are represented in the Figure 2.

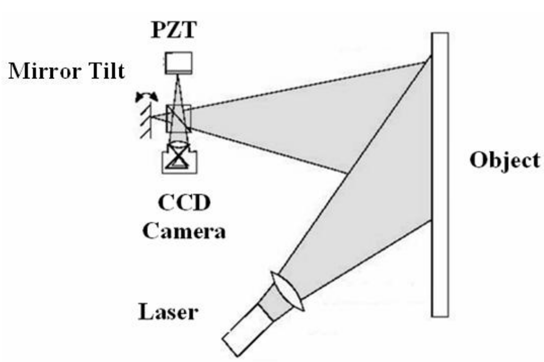


Fig. 2. Shearography set-up.

The surface under investigation is illuminated by an expanded laser beam which generates speckle patterns on the surface. Within the sensor head, which is shown in the Figure 3, a simple system of mirrors is designed to form the laterally sheared image of the surface. That is why, the interferometers for shearography are much more simple than those for ESPI, since they do not require a reference beam. It also makes shearography much more stable than the other speckle techniques [4].

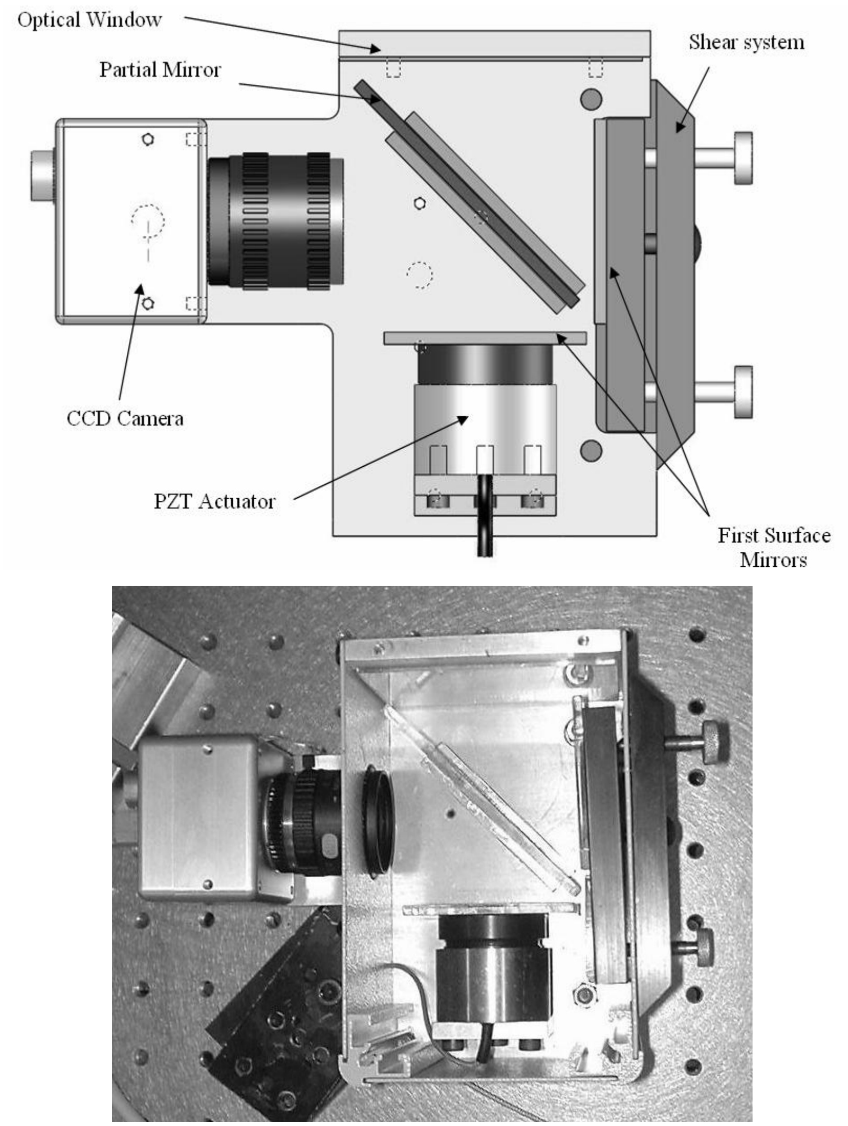


Fig. 3. Sensor Head

Two screws are used to control the direction and the amount of lateral shear that are imposed by the user to form the sheared image, which are also known as interferometric speckles [5]. Internal defects, if properly excited or loaded, can be revealed by their effects in the surface displacement field.

The fringe patterns are obtained by subtraction of the speckle patterns recorded before and after the thermal loading, employed to excite the delaminations in this work. Phase-stepping and phase unwrapping techniques are needed to calculate the phase distribution. In this work, the phase-stepping has been made through a mirror guided by PZT.

3. INTERFEROGRAM ANALYSIS

3.1 "Difference of phases" and "Phase of differences"

In this work two different methods are used to reconstruct the phase maps obtained with shearography. Both methods are represented by a diagram in the Figure 4.

In the first one, called "difference of phases" method, four phase shifted speckle-patterns images of the object are captured before deformation. From these fringe patterns, the undeformed phase map is computed by a standard phase shifting algorithm [8]. Then, after the object has been deformed, other set of four phase shifted images are captured and the deformed phase map is computed. The phase variation of the object can be calculated by the difference of two phase maps. The calculated phase change values obtained lie in the range ($-\pi$, π). A spatial phase unwrapping algorithm is used to remove the resulting 2π phase discontinuities [7].

The second method, known as "phase of differences" method, instead of recording a set of phase shifted images for each of the two deformation states, one records a sequence of images during the transient of temperature and a set of four phase shifted images while the object is at rest. The sequence of images captured are subtracted from each of the phase shifted images, resulting in a sequence of four phase shifted ESPI subtraction fringe patterns, like is shown in t he Figure 4. After smoothing, these sequence of images can be analyzed by a standard phase shifting algorithm to give the phase of differences maps for different times [10]. This approach has advantages in dynamic applications since only one image need to be recorded during the transient event and the remaining set of phase shifted images can be recorded while the object is at rest. The calculated phase change values obtained to different times lie in the range ($-\pi$, π). In this case a temporal phase unwrapping algorithm [9] is used to remove the resulting 2π phase discontinuities along the time axis.

3.2 Phase unwrapping

The process of adding the correct integral multiple of 2π to each phase value is known as phase unwrapping [10].

In order to unwrap a given phase distribution correctly, the original phase function must have at least two samples per cycle, corresponding to a true phase change between two neighboring sample points that lies in the range ($-\pi$, π).

If the requirement is satisfied for successive sample points along the time axis, then the phase at each point can be unwrapped as a function of time. The unwrapped phase change between two adjacent sample points, t and t-1, lies in the range ($-\pi$,π). When a phase difference value falls outside this range, it is therefore assumed to be due to a 2π phase jump falling between the two points. An appropriate multiple of 2π must be added to one of the sample points to bring it back into the correct range. This process is then known as temporal phase unwrapping.

If the requirement is satisfied for adjacent pixels in a spatial domain, then a spatial unwrapping can be carried out instead. In this work a 2D phase unwrapping algorithm called Flood Fill Algorithm [6] was used. This algorithm divides the phase matrix in weighted regions. The modulation is a measure of the local data quality and it is used here to separate the phase pixels into regions. These regions are grouped from the biggest value of the modulation to the smallest. The unwrapping process starts at the biggest modulation region and goes, step by step, until the smallest modulation region. That approach makes the whole unwrapping process more robust.

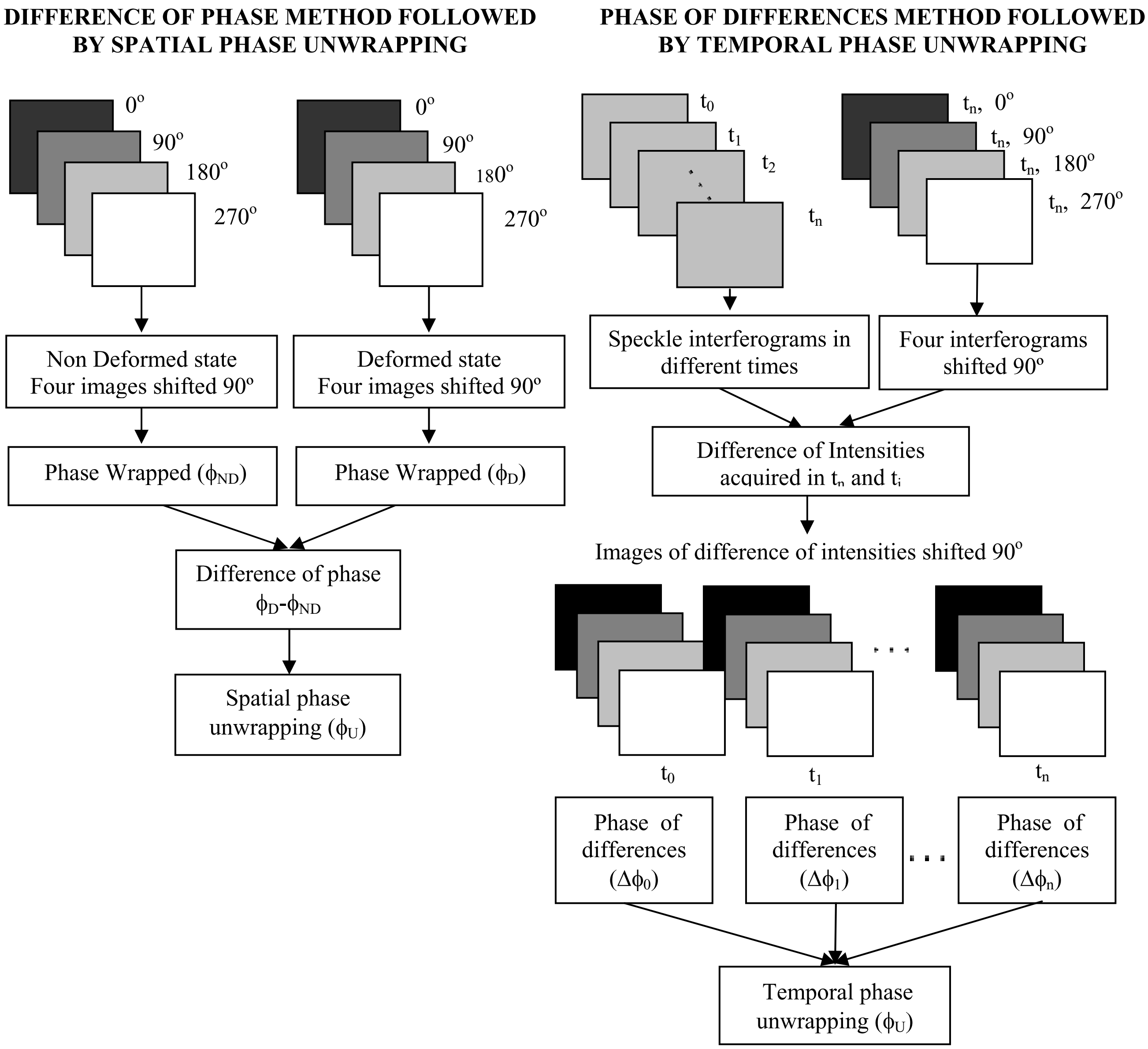


Fig. 4. Methods used to reconstruct the phase maps

4. EXPERIMENTAL SETUP

A steel pipe wrapped in four layers of composite material has been used as specimen in this work. This composite sleeve is used for pipe rehabilitation, molded "on-site" to repair external failures caused by corrosion and indentation. The pipe used in this work is employed in oceanic platforms for gas extraction. Thicker sleeves, with more than 20 layers, are applied on the pipes also for structural reinforcement after corrosion attacks [11]. With the purpose of testing the shearography system, an artificial delamination has been artificially introduced between the thin cover (4 mm) and the pipe as indicated in the Figure 5.

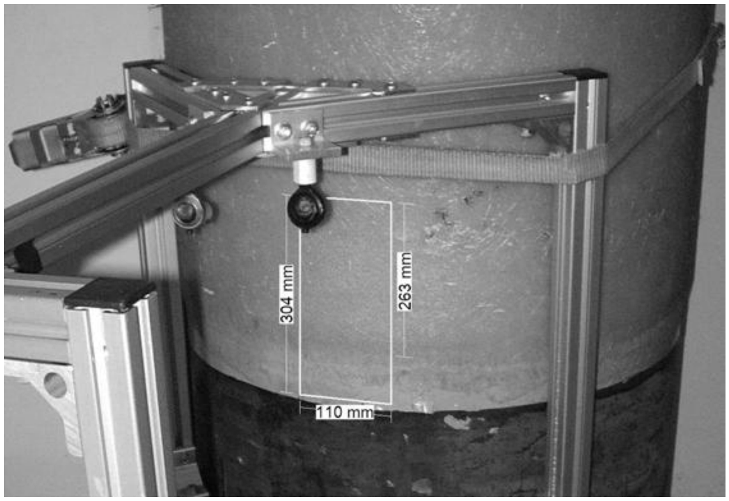


Fig. 5. Wrapped gas pipe

By means of a 500 W halogen lamp, thermal loads have been imposed to the composite sleeve to excite the delamination and create the two required states for shearography measurements.

The measurement system is composed by three modules: the illumination system, the sensor head and the processing software. The first two modules can be seen in the Figure 6. The sensor head, has been rigidly attached to the pipe aided by the aluminium structure and the yellow stripe what avoids vibration problems.

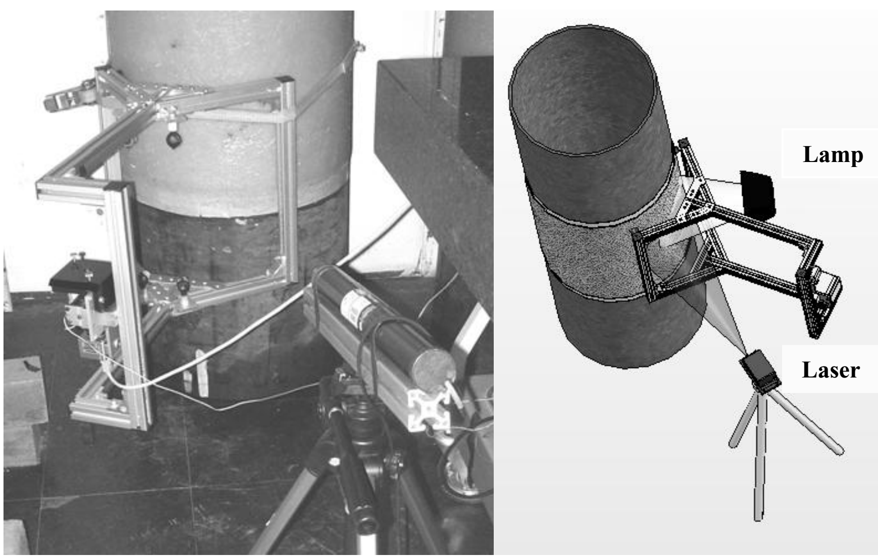


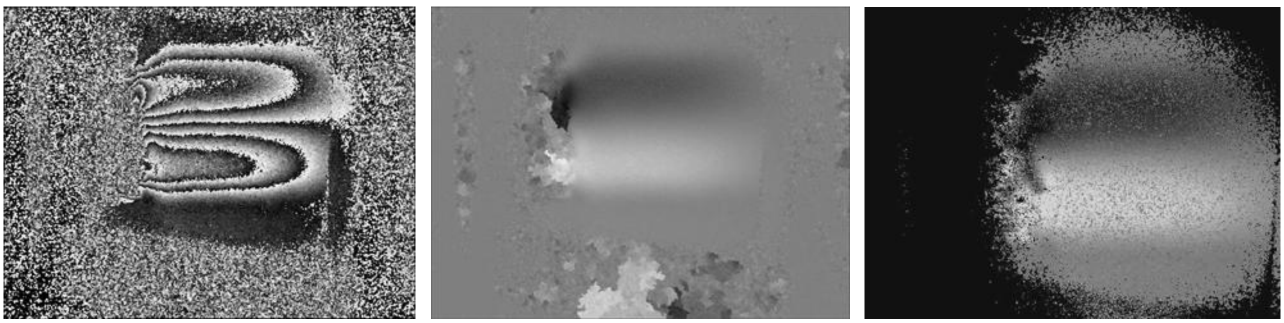
Fig. 6. Shearography measurement system attached to the gas pipe

5. RESULTS

Aiming to respect the sample conditions for Temporal Phase Unwrapping, a slow thermal load has been applied to the composite material covering allowing images acquisition with a frame rate of about 1 frame per second.

Two different experiments have been carried out. In the first one, the composite covering has been heated for 2 seconds only. After 10 seconds, the images acquisition has been started until the total cooling of the covering. The total cooling took a time of about 1 minute.

As shown in Figure 7, in this experiment both methods presented similar results. As expected, the phase map attained by Temporal Phase Unwrapping presents a lower signal-to-noise ratio when compared to the phase map obtained by the Spatial Phase Unwrapping method.



(a) (b) (c)

Fig. 7. (a) Difference of Phase Map (b) Absolute Phase Map by Spatial Phase Unwrapping
(c) Absolute Phase Map by Temporal Phase Unwrapping

Figure 8 shows the time domain behavior of three different points in the Absolute Phase Map obtained by Temporal Phase Unwrapping and demonstrates the correct phase unwrapping.

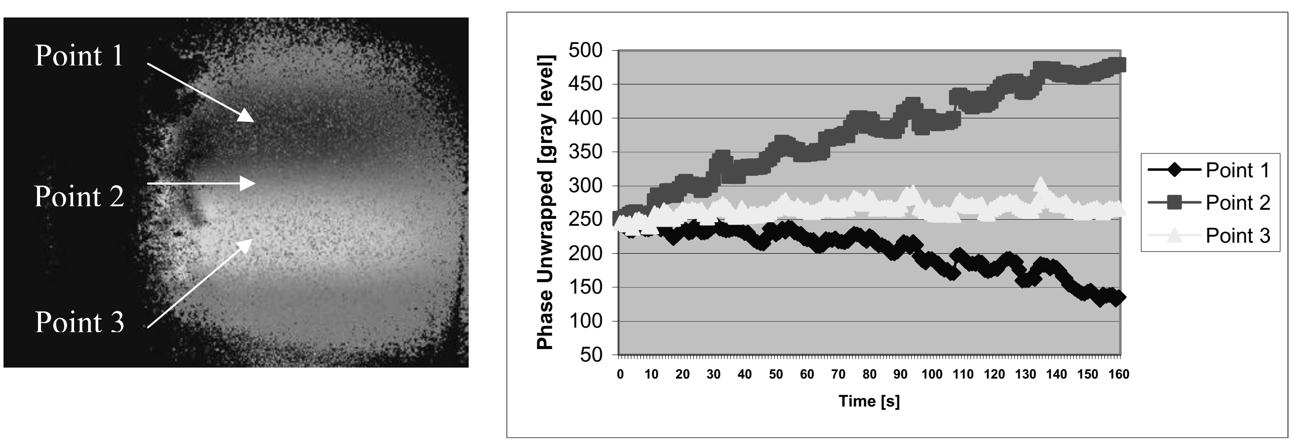


Fig. 8. Temporal Phase Unwrapping of three points

In the second experiment, the composite covering has been heated for about 15 seconds and the images acquisition was started after 1 minute. The images acquisition last for about 3 minutes. The higher temperature in this case, caused a higher concentration of fringes in the Difference of Phase map and the spatial phase unwrapping algorithm could not be applied.

The Temporal Phase Unwrapping method has not presented problems to perform the phase unwrapping in this case. In spite of the lower signal-to-noise ratio, it is more robust to perform the phase unwrapping when the thermal load provides a large amount of fringes. The results can be seen in Figure 9.


(a)

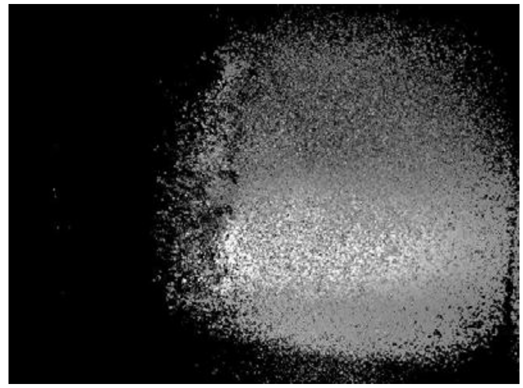

(b)

Fig. 9. (a) Difference of Phase Map (b) Absolute Phase Map by Temporal Phase Unwrapping

6. CONCLUSIONS

This work presents a comparison between two different methods for reconstruction of phase maps obtained using shearography.

In the first method, a Spatial Phase Unwrapping algorithm has been applied to a Phase Difference Map. This method demonstrated to be useful just in the first experiment, where a small thermal load has been imposed to the covering. In other words, the first method presents very good results when the number of fringes in the Phase Difference Map is small. In the second experiment the composite covering has been heated for 15 seconds and the phase map has been taken after the total cooling of the covering. For this reason, a large variation of temperature has been observed, and the phase map obtained with "Difference of Phase" method shows a high number of fringes. In this case the spatial unwrapped algorithm could not be applied because the poor image quality.

It is important to remember that the Difference of Phase method is very efficient in static measurements, where the phase maps are evaluated before and after the thermal load, and not during the cooling process of the structure. Indeed, the phase shifting suffers influence from the phase change caused by the thermal loading which has distorted the results. In this experiment it was not quantified the errors caused by this distortion, but it really exists.

In the second method, a Phase Map of the Differences has been evaluated by a Temporal Phase Unwrapping algorithm. By means of four reference images and many other images acquired during the cooling of the sleeve, it has been possible to monitor the whole cooling process. The second method attained good results in both experiments, independently of the amount of time. Generally, the Temporal Phase Unwrapping results present a lower signal-to-noise ratio when compared to the special case [10]. However, in dynamic measurements, where the specimen is influenced by a thermal loading which varies in the time, the second method is more robust. The method has been proving to be efficient in ever thermal loading level, since the minimum sample rate is been satisfied for the temporal phase unwrapping.

It is also possible, the use of more sophisticated Temporal Phase Unwrapping algorithms which take into consideration all phase values previously evaluated and not only the adjacent phase value [9]. In fact, these algorithms can improve the quality of the resulting image, since the intermediate measurements errors have no influence in the final result of the phase unwrapping.

REFERENCES

1. F. Santos, M. Vaz, J. Monteiro, *A new set-up for pulsed digital shearography applied to defect detection in composite structures*, Optics and Lasers in Engineering 42, 131-140, (2004).
2. C. Meola, G. M. Carlomagno, L. Giorleo, *The use of infrared thermography for materials characterization*. Journal of Materials Processing Technology 155-156, 1132-1137, (2004).
3. W. Steinchen, L. Yang, *Digital Shearography – Theory and Application of Digital Speckle Pattern Shearing Interferometry*. SPIE Press, Bellingham, Washington, USA, 2003.
4. Y. Y. Hung, H. P. Ho, Shearography: *An optical measurement technique and applications*. Materials Science and Engineering 49,61-87, (2005)
5. R. M. Groves, S. W. James, R. P. Tatam, *Shape and slope measurement by source displacement in shearography*. Optics and lasers in Engineering 41, 621-634, (2004).
6. A. Assundi and W. Zhou. "Fast Phase Unwrapping Algorithm Based on Grayscale Mask and Flood Fill", Applied Optics, Vol. 37, No. 23, 1998.
7. W. Osten and W. Juptner. "Digital processing of fringe patterns in optical metrology", Optical Measurements Techniques and Applications. P. K. Rastogi (Ed.), Artech House, Boston, MA, 1997.
8. K. Creath. "Phase shifting speckle interferometry". Applies Optics, Vol. 24. 3053 – 3058, 1985.
9. K. Creath. "Temporal phase measurements methods". Interferogram analysis. D. W. Robinson and G. T. Reid (Eds), Institute of Physics, Bristol, 1993.
10. J.M. Hutley, "Automated Analysis of Speckle Interferograms", Digital Speckle Pattern Interferometry and Related Techniques, P. K. Rastogi (Ed.), John Wiley & Sons Ltd, 2001.
11. http://www.rust.com.br/english/index.html. Visited in April 05, 2006.