STRAIN RECONSTRUCTION FROM DIC THROUGH DIFFUSE APPROXIMATION – APPLICATION TO DAMAGE DETECTION

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Abstract
Due to their material heterogeneity, the experimental study of 3D composites requires the use of specific strain measurements, like DIC. Moreover, when dealing with fatigue tests, the strain level remains very low, the derivation of strain field from the displacement field becoming a difficult task. In this paper, we propose a filtering tool based on the diffuse approximation and its extension to a space-time filtering and apply the method to the detection of early damage during fatigue tests.

1 Introduction

The study of the mechanical behavior of carbon epoxy 3*D* composites is a challenging task. Due to the structure of the fabric, the size of the Representative Volume Element (RVE) is about the centimeter scale, yielding a heterogeneous strain field at the measurement scale. The use of standard strain gauges for the characterization of their elastic properties is therefore not suitable. An appropriate alternative appears to be the use of Digital Image Correlation (DIC) [1] which yields the displacement field on the whole studied zone. For either qualitative studies or quantitative characterization, it can be interesting to derive the strain field from the measured displacement field. This operation is very sensitive to the measurement noise, even more during fatigue testing where the strain level leading to failure remains very low. A dedicated filtering tool based on the diffuse approximation [2] was proposed in [3] in order to construct the strain field from DIC fields, while controlling the reconstruction errors. When applied to quasi-static tests, it allowed detecting early damage in 3*D* composites [4]. In this paper, we take advantage of the large amount of snapshots from the fatigue test to develop a specific space-time filtering approach in order to improve the spatial resolution of the reconstructed strain fields. The two methods are compared and applied to quasi-static and fatigue tests on 3*D* composites, in order to detect the early damage before macroscopic cracking.

2 Diffuse approximation

The filtering operation is based on the use of a polynomial diffuse approximation, as proposed in [3]. The diffuse approximation yields a continuous field and its diffuse derivatives from a cloud of data points (here, the measurement points of the DIC algorithm defined) as the solution of a local weighted least square. In order to define the contributing zone to the reconstruction at a point (x_0, y_0), we define a neighborhood for each reconstruction point by introducing a length R such that every point with x or y closer than R to x_0 and y_0 are taken into account. The diffuse approximation field is then evaluated at the data points, so that the output data is of the same size as the input one. Classically, we use polynomials as basis functions, and degree 2 seems a good compromise [3].
The parameter R, controlling the span of the local contribution data zone, is the parameter to be tuned in order to control the filtering. As R increases, the random error decreases but the approximation error increases. A balance between both errors is thus to be found in order to

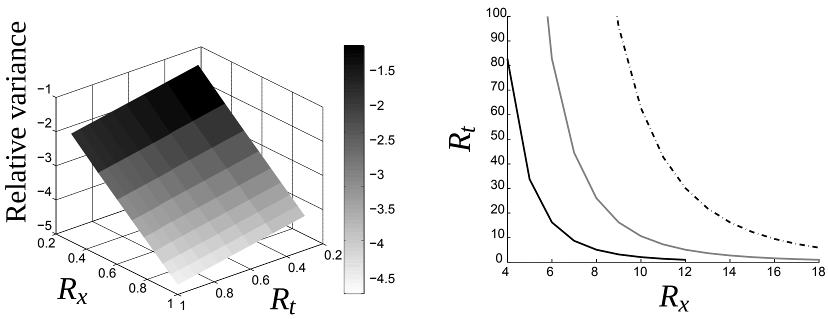
control the global error. Since the reconstruction operator is linear, one can study both the errors separately. For example, knowing the standard deviation on the measurements, one can estimate the standard deviation on the reconstructed strain. Assuming the measurement noise is a noise sample characterized by its covariance matrix $[C] = \sigma_m^2 [C_0]$ (in the case of a uniform white noise $[C_0]$ is the identity matrix), the covariance of the reconstructed strain field $\underline{\varepsilon}(\underline{x})$ can be expressed as:

$$\text{cov}(\underline{\varepsilon}(\underline{x})) = \left\langle \underline{\varepsilon}(\underline{x})\underline{\varepsilon}(\underline{x})^T \right\rangle = \left\langle M_\varepsilon \widetilde{U}_{\underline{x}} \widetilde{U}_{\underline{x}}^T M_\varepsilon^T \right\rangle = \sigma_m^2 M_\varepsilon C_0 M_\varepsilon^T \quad (1)$$

One of our goals is to control the quality of the reconstructed strain. As mentioned above it is possible to estimate the standard deviation of the output, based on some knowledge on the measurement. A pragmatic approach is proposed to control the error on experimental results, based on the idea that the standard deviation of the reconstructed field on a set of points is due on one hand to the noise and on the other hand to the mechanical heterogeneity of the strain field. Knowing the decrease of the standard deviation related to the noise, it is then possible to find a maximum R, such that for a greater R, there is a loss of mechanical information.

3 Space-Time Diffuse Approximation filtering

In the case where a large amount of images are available for a given test, it is possible to improve the spatial resolution of the reconstructed strain by filtering on space and time at once. The measured displacement fields are therefore stacked together along time, so that one now seeks a diffuse field of a three-dimensionnal variable $X = (\underline{x}, t)$. The local weighted least-squares are therefore formulated on space and time and one can tune both a radius in space, R_x and a radius in time, R_t .



(a) Relative random error on ε_{XX} (b) Iso-filtering curves

Figure 1. Filtering of the measurement noise for the space-time diffuse approximation

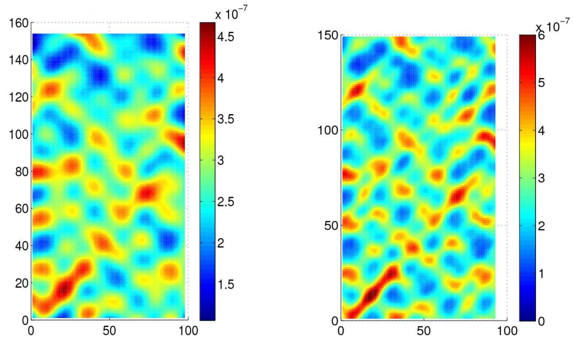
The characterization of the effect of the couple (R_x, R_t) on the filtering of the noise on the measurements can be studied from a theoretical point of view as for the 2D diffuse approximation. The figure 1(a) shows the relative variance of the output ε_{XX} field with respect to the input variance σ_m^2 in the case of a white noise on a log-log scale. One can note the effect of the time span is lower than the one of the space time [6]. In order to help in the choice of the couple (R_x, R_t), it is therefore possible to introduce isofiltering curves in the (R_x, R_t) plan enabling the same filtering of the noise. For a given level of filtering, one can now tune the time radius parameter in order to improve the spatial resolution of the filtering.

4 Applying the method on 3*D* composites for fatigue and quasi-static load

The two proposed filtering approaches are then applied to the study of carbon/epoxy 3*D* composites, whose heterogeneity implies large gradients for the strain field. During the test, all images are taken with a B&W cooled camera of 16 bits grey level, minimizing noise on the snapshot. DIC measurements are then performed on Correli Q4 [5].

4.1 Quasi-static test

In a first application, a quasi-static tensile test is studied, where one aims at detecting the local heterogeneities and damage within the material.

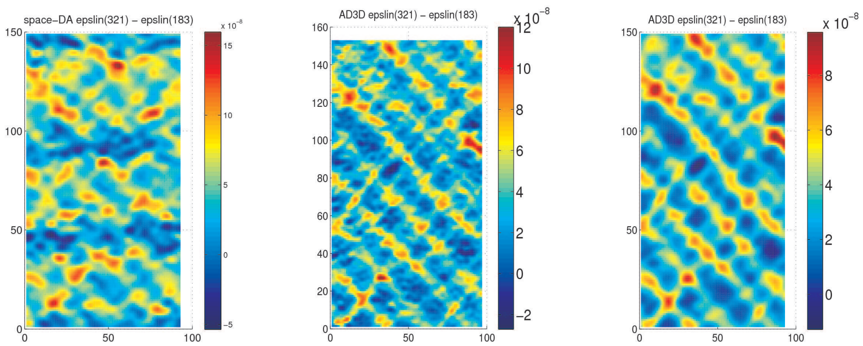


(a) $R_x = 12, R_t = 0$ (b) $R_x = 6, R_t = 16$

Figure 2. ε_{XX} : isofiltering reconstructions (a) space alone, (b) space-time

Figure 2 shows the ε_{XX} strain field in the elastic domain reconstructed with the same level of noise filtering with the standard diffuse approximation and the space-time diffuse approximation. It can be seen that the use of the latter improves the spatial resolution of the strain field.

Then, by studying the evolution of the strain field along the test, it is possible to track the local early damage during the quasi-static test. This can be performed by computing the discrepancy between the ratio of the strain to the load at various steps of the test, which will be refered to as $\Delta\varepsilon_{XX}$. Such a quantity should equal zero (within the precision due to the measurement noise) if there is no local evolution of damage. Therefore, its map is directly related to the spatial distribution of the damage, at least from a qualitative point of view.



(a) $R_x = 6, R_t = 0$ (b) $R_x = 4, R_t = 16$ (c) $R_x = 6, R_t = 16$

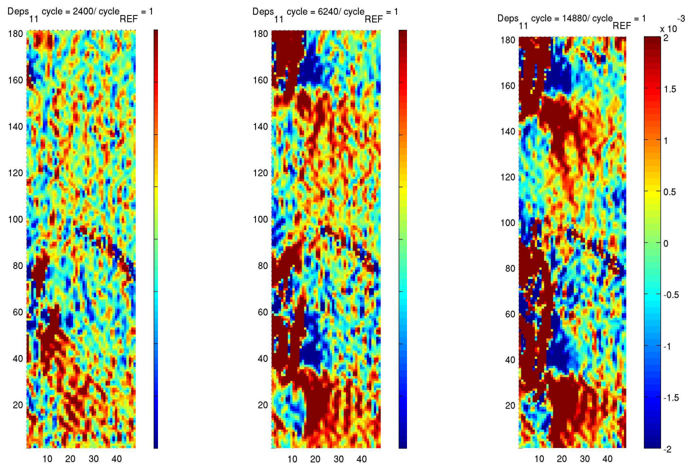
Figure 3. Incremental $\Delta\varepsilon_{XX}$

Figure 3 presents such a $\Delta\varepsilon_{XX}$ between two different steps of the test. Figure 3(a) corresponds to a space alone filtering, figure 3(c) is obtain through a space-time filtering with isofiltering parameters with respect to the space alone filtering and figure 3(c) is deduced from a space-time filtering with the same spatial span as the space alone filtering. One can note the spatial resolution is improved thanks to the isofiltering parameters. Considering the two filterings with the same spatial span, it can be observed that the taking into account of the time allows a relevant reducing of the noise.

The coupling of such information from kinematic observations with other measurements such as acoustic emission helps defining the ruin scenario of the studied 3D composites.

4.2 Fatigue test

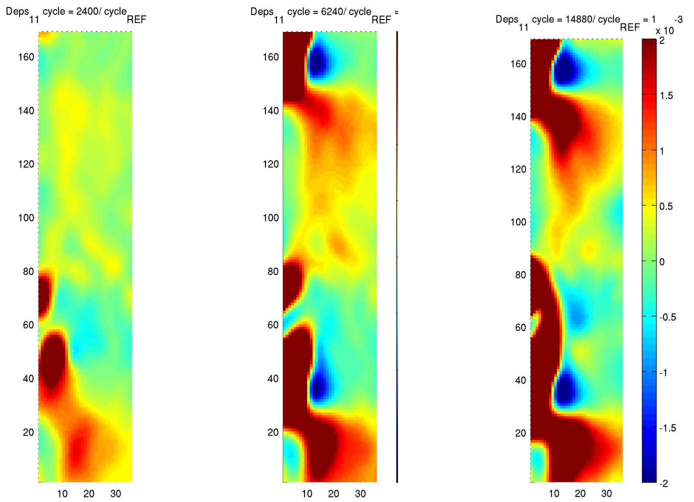
The same kind of study is performed on a fatigue test where about 1 500 snapshots are taken at the same load level every *n* cycles. This allows to perform a space-time filtering of the data in order to reconstruc the strain field. Let us not that the reconstructed strain field is not a standard Lagrangian strain field, since it is computed with respect to a loaded state. Nonetheless, this strain field yields some information on the evolution of damage during the test.



(a) $n°$ 100 (b) $n°$ 260 (c) $n°$ 620

Figure 4. ε_{XX} / snapshot number – Filtering parameters: $R_x = 3$, $R_t = 3$

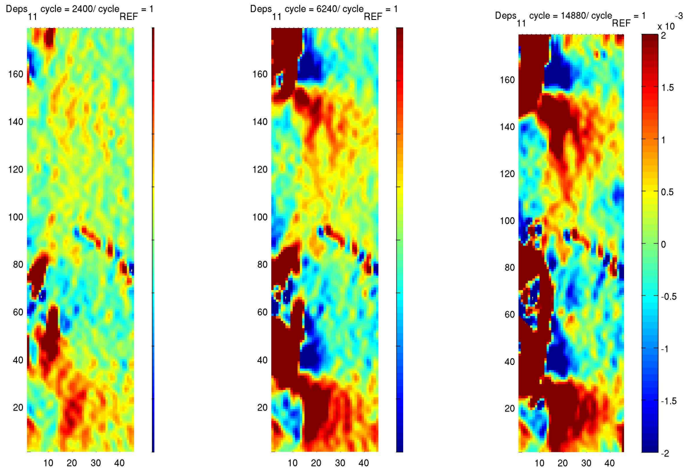
A first reconstruction is performed using a space-time diffuse approximation filtering with the following parameters : $R_x = 3$, $R_t = 3$, corresponding to rather low filtering. An exerpt of the results for three time steps is presented on Figure 4. One can see the strain field is very noisy and, even it some information on the localization of damage can be deduced, the field is globally spoiled by the perturbations.



(a) $n°$ 100 (b) $n°$ 260 (c) $n°$ 620

Figure 5. ε_{XX} / snapshot number – Filtering parameters: $R_x = 9$, $R_t = 3$

A second reconstruction is thus performed increasing the spatial span while keeping the same time span, $R_x = 9$ and $R_t = 3$ are chosen. The results are presented for the same time steps on Figure 6. Now, the noise has been mainly filtered and one can observe the strain field, but with a very poor



(a) $n^\circ\,100$ (b) $n^\circ\,260$ (c) $n^\circ\,620$

Figure 6. ε_{XX} / snapshot number – Filtering parameters: $R_x = 4$, $R_t = 80$

spatial resolution. From this reconstruction where one can considered the filtering of the noise as reasonable, a third reconstruction is performed based on the isofiltering curve associated with the current values of (R_x, R_t). The values of $R_x = 4$ and $R_t = 80$ are chosen in order to decrease the spatial span as much as possible while keeping a reasonnable value of the time span. The local least-squares asociated with the diffuse approximation are therefore performed for each reconstruction point on a data set of $7 \times 7 \times 159 = 7791$ measurement points, allowing a good filtering of the noise, while keeping a reasonable spatial resolution. A specific numerical implementation is used in order to keep the calculation time affordable.
The results are presented on Figure 6 where it can be observed the filtering of the noise is the same as on Figure 5 but the spatial resolution is largely improved. Here again the coupling of this information with other experimental data, including thermographic field measurement can help understand and propose a ruin scenario for the considered 3D composite.

5 Conclusion

In this paper, we proposed a tool to reconstruct the strain field from the displacement field obtain for example by digital image correlation. Such a task is not trivial because, the measurement noise needs a particular attention. The proposed tool is based on the diffuse approximation and was first developed in two dimension (in space) then extended to the three dimension case through a space-time filtering. The taking into account of the temporal dimension allows a significant improvement of the spatial resolution while keeping the same level of filtering for tests where the time evolution is slow enough with respect to the time rate of the snapshots. Let us note that such a tool could be applied to thermographic or tomographic measurements.
The tool has then been succesfully applied to the characterization of the evolution of damage in 3D composites. Som criteria of qualitative detection of the damage have also been proposed and compared for various types of filtering, confirming the interest of a space-time filtering.

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