Strain fields evaluation on aerospace structures using Digital Image Correlation aimed at Structural Health Monitoring

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ABSTRACT

Lightness of structures is a primary requirement in Aerospace Engineering. Therefore the typical structural elements used in this field are thin plates, stiffeners, ribs and fasteners assembled to resist very high loads but weighting as low as possible. Wings, fuselage, tail and control surfaces are built with longitudinal stiffeners and transversal ribs enclosed by a thin shell. These shells guarantee the aerodynamic properties and carry part of the shear stresses while the internal elements satisfy the remaining structural requirements. A similar philosophy is used in spacecraft design. The use of thin-walled reinforced shells is generally very convenient, but it implies a higher difficulty during the design process. Instabilities can arise very easily in these structures, since very thin elements are used, causing undesired consequences, like structural damages or failures. It is also worth noticing that aircrafts and spacecrafts suffer problems of fatigue, because the loads are not static and vary widely and frequently during the lifetime of the vehicle leading to cracks propagation. For these reasons analytical and numerical result obtained during design must be validated by some kind of experiments involving several loading modes. In all of these tests, the experimental measurement of full stress and strain fields would be particularly interesting. These fields often show irregular patterns, seen around cut-outs, structural imperfections, damaged areas including delaminations in composites plates or in case of instabilities. The goal of this paper is to present the employ of a state-of-the-art Digital Image Correlation system to evaluate the full stress and strain fields of a thin-walled structural item under fatigue load cycles, comparing the optical measurements with other inspection techniques. Furthermore a preliminary numerical analysis is presented in order to verify the strains levels and their discontinuity patterns around a simulated delamination when a small composite plate is subjected to different loads conditions; these levels and patterns will be then verified during future experimental activities by DIC. This simple but still effective numerical investigation shows the potentialities of an experimental full strain field availability before and after a delamination occurs for designing a Structural Health Monitoring system in order to monitor, as example, the damage propagation during fatigue tests on composites parts in a laboratory environment, with low time consumption.

Keywords: Digital Image Correlation, Aerospace structures, Fatigue tests, Structural Health Monitoring.

1. INTRODUCTION

Lightness of structures is a primary requirement in Aerospace Engineering, therefore the typical structural elements used in this field are thin plates, stiffeners, ribs and fasteners assembled to resist very high loads weighting as low as possible avoiding payload penalization. For instance, an aircraft is made of several different thin-walled shells [1]. Wings, fuselage, tail unit and control surfaces are built with longitudinal stiffeners and transversal ribs enclosed by a thin shell. These shells guarantee the aerodynamic properties while the internal elements satisfy the structural requirements. A similar philosophy is used in spacecraft design. The use of thin-walled shells is generally very convenient, but it implies a higher difficulty during the design process. Instabilities can arise very easily in these structures, since very thin elements are used. Thus structural engineers must take into account these phenomena to prevent undesired consequences, like structural damage or failure. Furthermore, the theory that describes thin-walled structural elements is non trivial and requires an in-depth analysis of non-linear equations. This often leads to the use numerical methods to solve this specific kind of mathematical problems. Another key aspect is the designing of structures with a wide use of cut-outs. They are necessary to reduce weight, to allow the passage of hydraulic lines, fluids or wires, to allow inspection and leave certain internal spaces accessible but this induce obviously a weakening of the structure and leads to stress concentration around the holes. That is why their sizing is particularly complex. Finally, aircrafts and spacecrafts due to their specific load conditions and structural configurations, suffer problems of fatigue. This might lead to cracks and additional stresses concentration which may cause the failure of the whole structure. On this specific aspect are based most of the contents of this paper.

Testing of these structures typically involves several loading modes. In all of these tests, the full stress and strain fields are of particular interest especially if experimentally measured, often for validating numerical results. They often show irregular patterns, seen around cut-outs or in case of instabilities. The full strain field measurement can show stress concentration around certain points of the structure not predicted by analytical or numerical models. This allows the engineers to mitigate stresses concentration and consequent cracks onset by reinforcing the structure or by applying structural redundancies principles and preventing long term damage due to fatigue. The goal of this experimental thesis is to use the Digital Image Correlation Theory to evaluate the full stress and strain fields of a material under fatigue load conditions [2]. Some results will be presented obtained for a metallic plate under fatigue load in a fatigue test machine and, following, a numerical study will be shown aimed at evaluating the expected strain discontinuities and levels due to a delamination in a typical Carbon-fiber reinforced plate under load. This second part of the work is finalized to evaluate the load levels necessary to induce a strain field average level inside the composite plate falling within the measurement capabilities of the digital interferometry.

In principle, by measuring experimentally a full strain field using digital interferometry on a delaminated composite plate under static load (tension, compression or shear) it should be possible to detect the presence of a delamination inside the lamination sequence, since it should have effect also on the strain fields of the external lamina, that is exactly the field that the optical interferometry is capable of measure. This concept, anyway, has to be first investigated numerically in order to understand, for a specific panel and lamination sequence, which is the load necessary to enhance the strain field on external lamina up to a level that is high enough to be detected by the DIC being above its intrinsic measurement noise. In this case and for similar load levels the delamination should be recognized by a typical strain discontinuity pattern. The second part of this paper aims to demonstrate numerically this possibility in order to design the proper experimental set-up for following validation (that is not part of this work). The immediate benefit of this approach could be a faster and cheaper monitoring of delamination extension during fatigue loads testing of aerospace structural components, when typically a “no-growth” delamination behavior needs to be demonstrated to fulfill the damage tolerance design philosophy [3], [4]. Actually the delamination monitoring during fatigue tests, even on big structural items, requires under the current procedures, a load cycle stand-by period during which ultrasound based testing of the delaminated area are carried out; this procedure is obviously time consuming and often need for complex set-up arrangement in order to permit the access of UT operators to delaminated areas. It results obvious how optical based measurements could reduce drastically the level of complexity of the tests and, being fundamentally based on full strain measurements of the loaded structure under test, they would not require anymore to stop fatigue testing having the capabilities, under certain load levels, to monitor in real time delamination extension during their load cycles. The same approach could also be, in principle, effective to evaluate whatever structural “perturbation” altering the original strain field in a reinforced thin walled structure, like, as an example, a stringer de-bonding on a stiffened plate; this would go towards the implementation of a continuous Structural Health Monitoring system within fatigue testing characterized by lower time consumption if compared to actual non-destructive analysis techniques [5],[6].

2. DIGITAL IMAGE CORRELATION

Digital Image Correlation refers to non-contact methods that acquire images of an object and perform their analysis to extract full field deformation and motion measurement. One of the most common uses random speckle patterns and compares sub-regions (facets) throughout the image to obtain full field measurements. The speckle patterns are typically painted on the surface of the object to be examined. In other applications they can be printed or glued on the body using particular techniques. In this work an ARAMIS 3D ZEISS GOM System [7] has been employed to compute the strains on the surface of a body using the measured displacements detected by analysing pictures taken with two high refresh rate cameras. As additional requirements there is of course the need of a speckle pattern applied on the test object, as already explained above, and a proper lighting setup.

DIC is based on the principle of Image Matching which is a branch of computer vision, used in many practical application. For example it is employed in industrial processes, stereo vision applications, or plate recognition for road cameras [8]. Its goal is to find correspondence between points in multiple different images, allowing evaluation of motion vectors. From these, it is possible to derive displacements and strains. In our case, given a set of sequential images, Image Matching allows pattern recognition and motion analysis. Furthermore, we can use it to analyze pattern deformations applied on specimens. To accurately measure the stress-strain curve for many materials, the algorithm must be precise enough to resolve strains on the order of 10−5 mm/mm [9]. In Image Matching, colors are not of interest. Thus, grayscale images are used and each pixel is assigned with a gray value. This implies that the same gray value could be found in different pixels on the same image. When analyzing a second image, a unique correspondence of a pixel of the first image in the second one cannot be established. This happens because its gray value will be found in several pixels of the second image, making the correlation not bijective. Even considering a neighborhood doesn't solve the problem. For example, if a line is not entirely captured in the frame, it is impossible to properly track the motion of a point along the line itself. This happens because each point of the line has the same gray value. Thus, we define the aperture, as the subset of points used to track the object. In the previous example, including the entire line with its extrema solves the problem (See fig. 1).

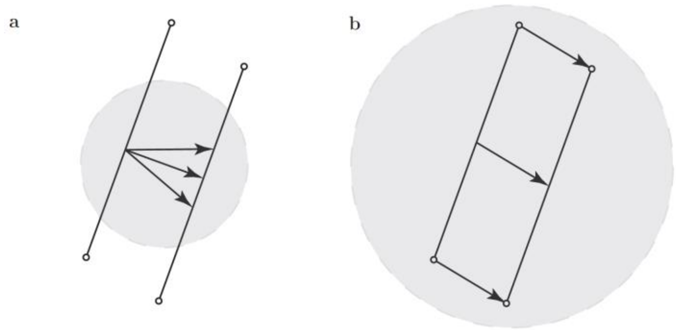

Figure 1: a) The aperture doesn't include the extrema, so the tracked point can be associated with any point on the line. b) The aperture includes the extrema, so it is possible to track the motion of the whole line.

For more complex 2D objects with a grid pattern, the problem becomes pattern recognition. This introduces the repetition of patterns on top of single gray values. It is imperative to include the whole grid in order to have a complete view of the pattern. Similarly, for a continuous 2D object under deformation, it is impossible to measure its shape variation without including it completely in the frame. This still doesn't allow strain measurements. If the object has the same gray value across its whole shape, it is impossible to perceive any deformation.

The use of a speckle pattern solves the problem uniquely. The ideal texture should be isotropic and stochastic (non-periodic), as shown in fig. 2. The pattern is often made of black and white paint, which adheres very well on the object surface and allows precise strain and displacement evaluation during loading. A good speckle pattern has a high information content. Moreover, the pattern is continuously distributed on the surface, allowing full field measurement. Of course, a high quality pattern will lead to higher accuracy [10].

Figure 2: Example of a typical high quality speckle pattern on a flat plate

Within the authors' laboratory a state-of-the-art 3D DIC system by ZEISS-GOM is available named Aramis adj SRX 12 Mp consisting of:

- Two high-resolution CMOS sensors mounted on a beam with a graduated scale to align them in the correct position.
- A controller to allow coordination with a load cell.
- A high-performance computer to process images using the application software GOM Correlate Pro.
- A laser pointer for sensors positioning and adjustments.
- One or multiple LED lights to illuminate the test object.

Figure 3: The ARAMIS Adjustable Base Camera

The system is capable of analyzing object deformations, rigid body movements and the dynamic behavior of test objects in three-dimensions. To this end, the software requires reference points or a speckle pattern to be applied on the part. They must be recognized in an initial image. This image will then be used as a template for comparison with following images, as explained above. The system can capture static and dynamic loading tests. Therefore, reference points coordinates or speckle pattern surface coordinates are measured over time. Then, displacements, strains and derived values such as velocities or accelerations are computed. The temporal resolution depends on the frequency used for the image recording. The system is able to acquire many measuring volumes at customized sample frequencies up to about 2000Hz and depending from the required exposure times or, as a consequence, from the lighting conditions and speckle pattern quality. Within this work only static acquisitions have been carried out.

3. FATIGUE TESTS MEASUREMENTS BY D.I.C.

First objective of the present work was to employ the DIC in order to acquire the strain concentration areas associated to a typical crack propagation during fatigue tests on a simple metallic flat plate. This would have permitted to easily measure the crack size increment during the fatigue tests and to compare it with the dimensions measure by classic visual inspection. The plate dimensions were 400 x 180 mm with a 2 mm thickness, and the set-up consisted in a combination of many sensing systems (including piezoelectric patches and optical fibers with Fiber Bragg Gratings); it was designed and implemented for comparing measurements from all the sensing systems within a wider European research project. Here only the comparison between visual inspection and DIC measurements will be reported.
Following is possible to see some pictures of the test set-up and test machine. The speckle pattern was created on an area of 200mm height around the original 10mm initial crack for the full width of the panel; the DIC then reconstructs the displacements (as well as the strain) field of the painted area providing continuous strain levels around the crack when the panel is loaded within the fatigue tests at varying load levels chosen to let the crack propagate in stable conditions.

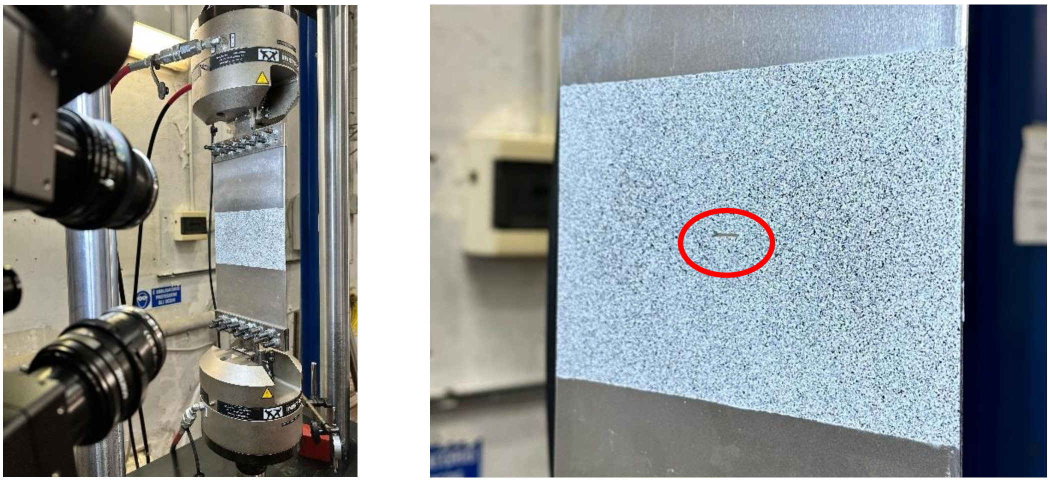

Figure 4: The Panel under test (with the area painted with the speckle pattern) and the original 10mm crack (in the red ellipse)

During the fatigue test campaign loads amplitudes have been chosen ranging from 10kN to 100kN permitting the crack to propagate in stable way and in the following images some results are presented where is possible to see how accurate is the representation of the crack boundaries obtained by the DIC as well as the comparison of the crack dimensions as measured visually and by the DIC strain level measurements.

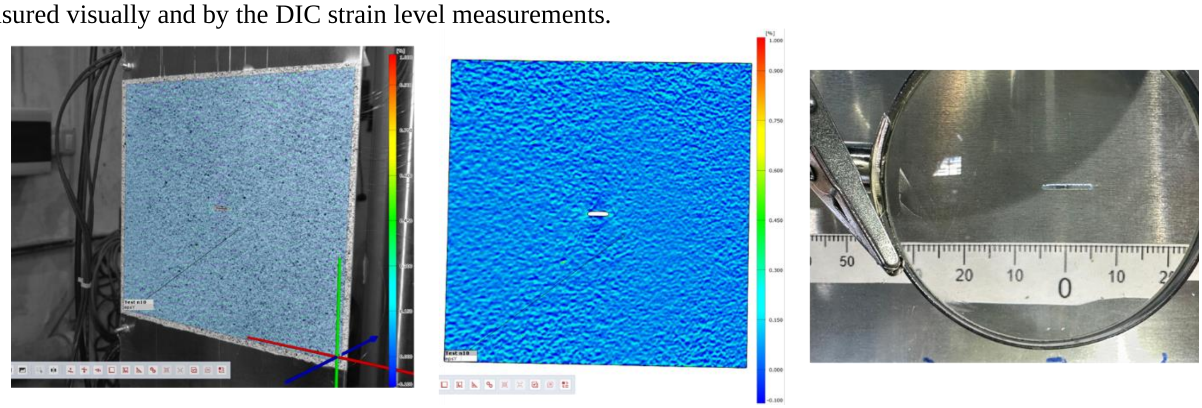

Figure 5: Measurements after 10kN cycles (left: camera image – center: processed top image – right: back plate crack visual measurement)

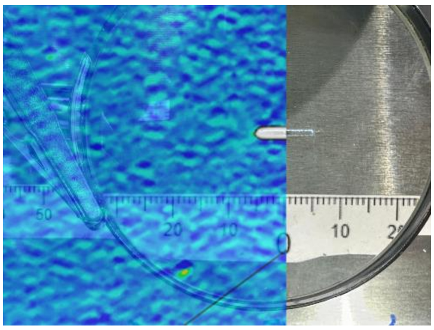

Figure 6: Comparison of measured crack dimensions after 10kN cycles

From images 5 to 10 it came out intuitively that DIC permits immediate measurement of the crack elongation, evidentiating the stress intensification area around crack tip while visual inspection, even magnified, hardly permits the exact measurement of the crack elongation.

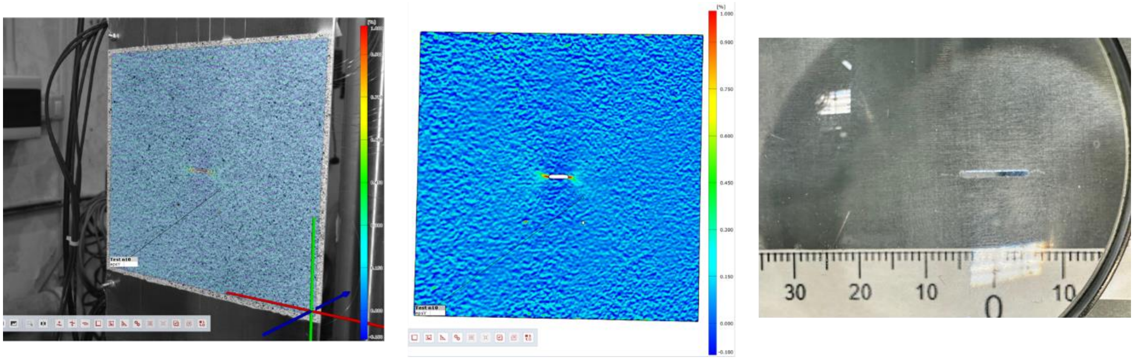

Figure 7: Measurements after 35kN cycles (left: camera image – center: processed top image – right: back plate crack visual measurement)

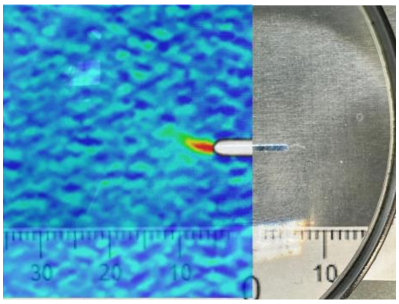

Figure 8: Comparison of measured crack dimensions after 35kN cycles

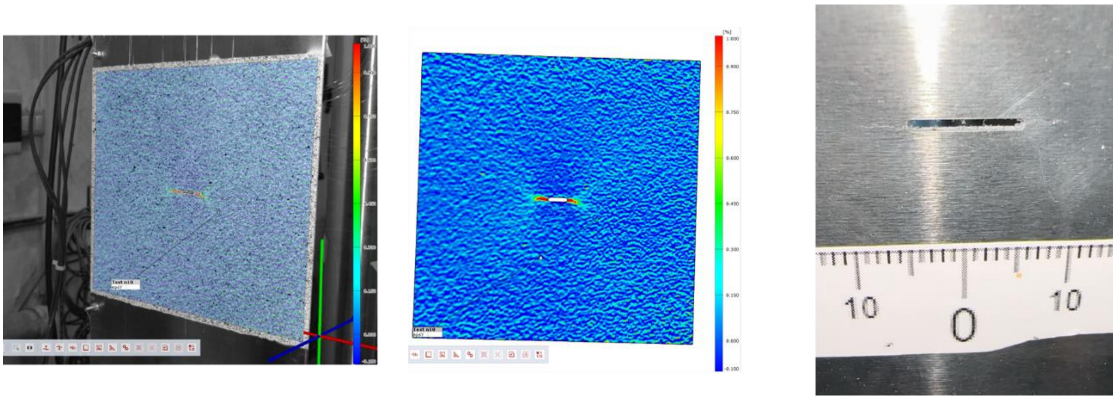

Figure 9: Measurements after 50kN cycles (left: camera image – center: processed top image – right: back plate crack visual measurement)

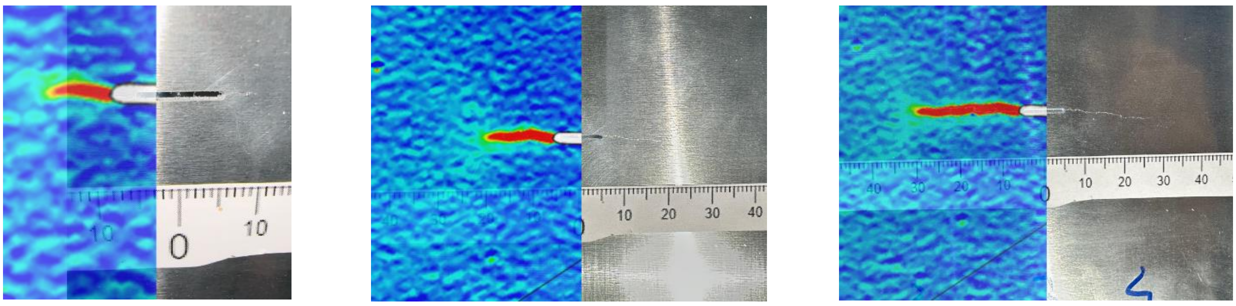

Figure 10: Comparison of measured crack dimensions after 50kN (left), 80kN (center) and 100kN (right) cycles

4. NUMERICAL MODEL OF A FLAT COMPOSITE PLATE FOR EVALUATING DIC CAPABILITIES IN DELAMINATIONS INDUCED STRAINS FIELDS VISUALISATION

The final part of this work consists in a numerical analysis conducted on a carbon fiber reinforced composite plate (GFRP) loaded in tension before and after a delamination has been simulated between two laminas of it lamination sequence.
The plate modeled consisted in an 8 plies symmetrical and balanced lay-up ($90/-45/45/0_S$) clamped on one side and loaded with an overall tension load of 14.4kN on the other side homogeneously distributed on the free side nodes. Each ply has been modeled by solid elements and 3D orthotropic material simulating the elastic properties of the composite material. The delaminated model has been recreated by degrading the elastic properties at 40% of the original ones on the third ply (45° orientation) on a small area of 20x20mm in the middle of the plate. Following are some pictures of the plate section and the delaminated area.

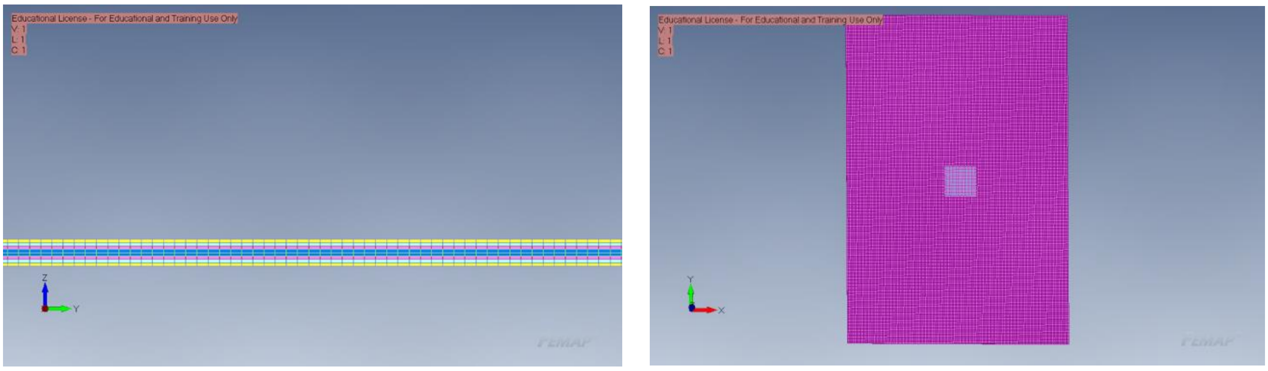

Figure 11: Cross section of the composite plate lay-up (left: different colors are related to different ply orientation) and delaminated area on the second ply at 45° orientation

Applying the 14.4kN traction load on the free side of the plate it has been possible to require as output the strains of the top ply of the plate, in order to visualize the strain field that a potential interferometry system should be able to measure, before and after the simulated delamination accurs.

Next figures presents the strain field levels (normal Y strain and XY shear strain) on the integer plate.

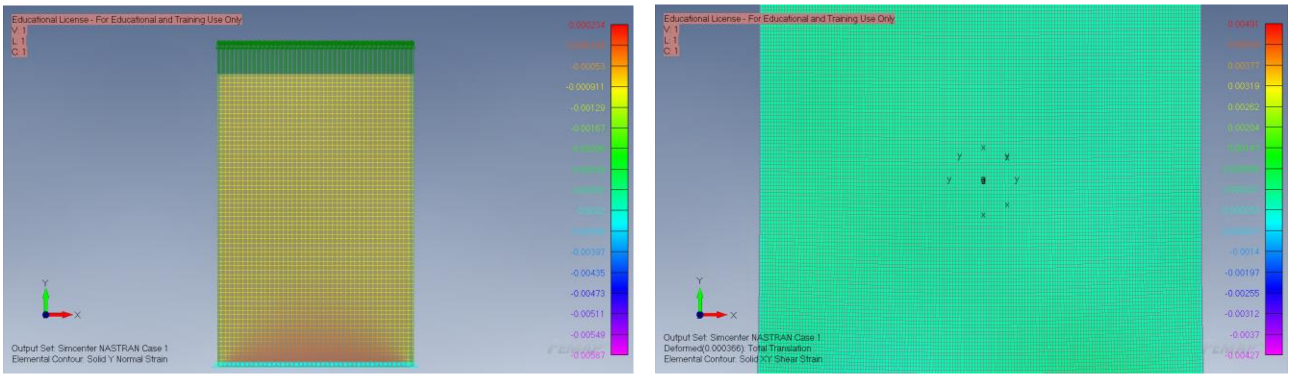

Figure 12: Strain fields on the top ply of the plate when a 14.4kN tension load is applied (left: normal Y strain – right: shear XY strain)

In figure 13 are than presented the strain field levels (normal Y strain and XY shear strain) on the top ply of the plate with the previously described delamination.

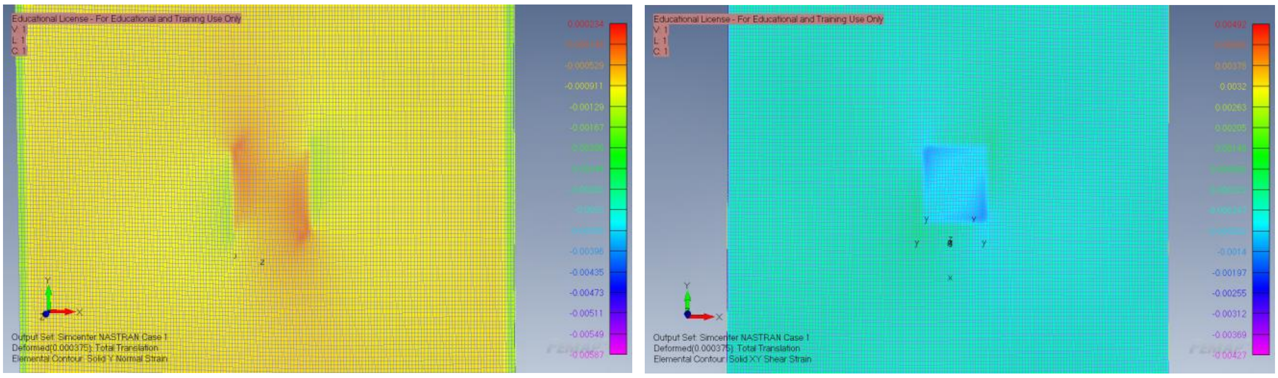

Figure 12: Strain fields on the top ply of the plate when a 14.4kN tension load is applied (left: normal Y strain – right: shear XY strain) – *DELAMINATED CONDITION*

Is possible to notice that, for the analyzed load condition the strain levels fall within a range theoretically measurable by the digital interferometry system and, furthermore, that the presence of a delamination should create, also in this case, in the area surrounding the delaminated section, a concentration of the stresses (both normal and shear ones) also on the external ply that is of our interest for optical investigation. In principle, therefore, it should be possible by the presented SIC system to detect, localize and also delimitate the presence of a delamination inside a laminated composite plates if the plate itself is subjected to medium loads like the one considered. It could be even possible to enhance the effects of the presence of the delamination on the external strain fields by increasing in principle the load value or modifying the load condition (for example loading the plate by in-plane shear). Further activities will be devoted in more numerical investigations and, following, in experimental assessment of the presented approach by our DIC system loading before and after an impact inducing barely visible damages (delaminations) on a carbon-fiber reinforced plate.

5. CONCLUSIONS

This paper presented the preliminary activities related to the use of a state-of-the-art Digital Image Correlation system for monitoring crack propagation during fatigue tests on cracked metallic plates as well as on delaminated carbon-fiber reinforced plates. Experimental results were already presented for the first case while for composite plates a numerical investigation has been presented aimed at analyzing the potentialities of DIC for detecting full strain fields induced on the top ply of the plate by an internal delamination when the plate is externally loaded.
Both experiences brought to promising results and the activity, only at its initial stage, will continue during next months to investigate the possibility of employing DIC for continuous monitoring of delaminated area in aerospace composites components during fatigue tests within a damage tolerance design philosophy.

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