ON-LINE DAMAGE MONITORING AND EVALUATION IN CFRP AEROSPACE STRUCTURES DURING MECHANICAL TESTING

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Abstract. Mechanical testing of aeronautic composite structures comprise the evaluation of damage evolution by NDT methods, like ultrasonics. Usually, scheduled inspections are performed during fatigue testing in order to assess damage progress. Registers are obtained during test stops and recorded directly on part or C-Scan file if feasible (complex geometries, no access for encoders, etc.). In case of static testing, in-live thermographic inspections can be performed for detection of fiber breakages and/or appearance of delaminations. Data storage results a difficult task during fatigue testing since test execution period comprise several months.

The aim of this study is to develop an innovative Non-Destructive Testing (NDT) system for on-line monitoring of composite aircraft components during fatigue mechanical tests execution. A feasibility test campaign including different NDT methods (Air coupled Ultrasonics, Wheel Probe Ultrasonic phased Array, Thermography…) has been performed. Once NDT method is selected, the conceptual approach of the system has been evaluated during mechanical testing of large composite panels, including system geometrical configuration, data analysis, automatic detection of damage event and data storage, etc. Finally, a conceptual system for CFRP cockpit evaluation is presented.

1. Introduction

Structural testing is an integrated part of aerospace product design, development and manufacture. It is an essential step to ensure performance, quality, safety and reliability in the final product. Structural tests on CFRP elements usually require Non-Destructive Testing (NDT) during execution to check the behaviour of the component under these degradation phenomena and the potential appearance of failures in the material.

Artificial defects, like impacts of different energy producing delaminations/cracks, are introduced artificially into the structure. Therefore, it is mandatory to continue performing NDT inspection because it will allow following up defect evolution and inform about acceptable limits before producing a catastrophic failure in the component.

In general, these inspections are carried out manually, applying conventional ultrasonic technique and, therefore, no registers of the inspections are available (these are directly marked on the component) and require human presence whenever the NDT test is needed during the process.

The aim of this work is to develop a system to perform NDT examinations during structural test execution of CFRP aircraft cockpit, in an automated manner, and including on-line transmission of the results through web communication protocols. The expected advantages of this approach are: (i) The total test time reduction and saving in man-hours of NDT operators, taking into account that tests are running 24 hours a day and NDT actuation can be required anytime (it means, fully operator availability); (ii) The possibility of a very early detection. As no human presence is necessary, the number of inspections could be larger, improving process quality without increasing costs.

A feasibility test campaign has been performed including different NDT methods, like air coupled ultrasonics, conventional phased array ultrasonics, thermography and laser shearography. For the tests on large compilation of samples and CFRP cabin have been utilized. Once the most suitable NDT method is selected, the conceptual approach of the system has been evaluated during mechanical testing of composite panels, including system geometrical configuration, data analysis, automatic detection of damage event and data storage, etc. Finally, a conceptual strategy for the evaluation of CFRP cockpit is presented.

2. Experimental Methods

2.1 Materials

Several parts from CFRP cockpit (manufactured by AIRBUS DS / formerly EADS-CASA) have been evaluated within this work. Those are depicted in Figure 1, indicating as well the cockpit areas where the different parts were extracted from.

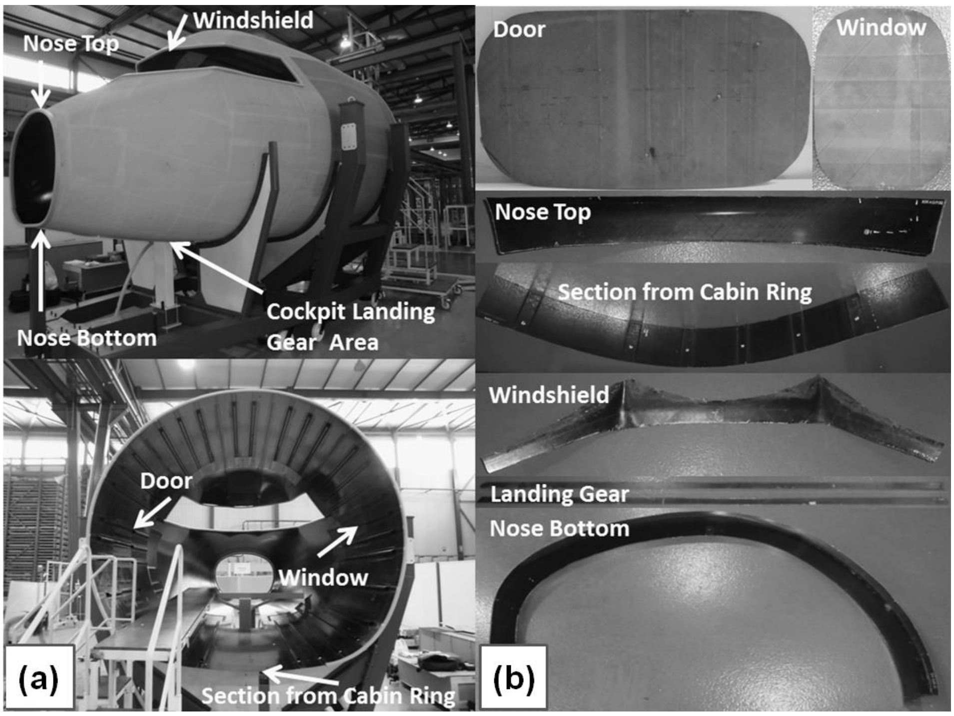

Fig. 1. (a) CFRP cockpit views with indication of main area for part preparation; and (b) inspected specimens.

2.2 Testing methods and equipment

Infrared Thermography: IRT is a contactless non-destructive method, capable of tracking both sub-surface and surface indications. IRT is characterized by its speed, versatility and easy to use, offering interesting results for defect detection in composite materials, between others. IRT can be classified in “active” and “passive” depending on excitation strategy. During active inspections the part is stimulated by an external thermal source. The heat flux is modified by the internal structure/flaws within the part and reflected to the specimen surface, where the different indications can be tracked [1-2]. For the case of passive testing, the component temperature is monitored, where the apparition of hot/cold areas is analyzed and related to e.g. flaw apparition during mechanical testing [3].

A FLIR SC7000 camera (with thermal sensitivity of about 18 mK) has been utilized. Image adquisition has been performed by FLIR Altair and IrNDT software for passive and active inspections, respectively. Two 2.5 kW halogen lamps have been utilized for thermal excitation (active IRT).

Laser shearography (LS) is an optical interferometric technique, which provides surface deformation information of an element in real time. The operation consists in illuminating the object under study by using an expanded laser, at different stress conditions. The last one, can be introduced in the test part by a partial vacuum, thermal excitation or vibration. The stress induces the deformation of object surface, which is locally modified by subsurface defects such as delamination or debondings, for composite or sandwich structures, respectively. After a quick comparison between both stress conditions, by calculating the induced deformation gradient, indications are easy detected [2,4].
For this test, a Q-800 High Solution Shearing Sensor with 4 Diodes Lasers have been utilized (DANTEC Dynamics). Thermal excitation has been applied during testing.

Ultrasound (UT): This method is based on elastic ultrasonic waves that pass through a material being examined. Material discontinuities are detected by the interaction of the waves with these discontinuities. For conventional UT [5-6] the ultrasonic waves used for flaw detection are generated and received by small probes called ultrasonic transducers, when it is excited by an electrical pulse it generates sound waves, and when it is vibrated by returning echoes it generates a voltage. The active element, which is often referred to informally as the crystal, is protected from damage by a wearplate or acoustic lens, and backed by a block of damping material that quiets the transducer after the sound pulse has been generated. Air-coupled UT [7] testing in transmission mode is based on the measurement of ultrasonic energy, passing through a test component placed between the transmitter and receiver transducers. A component containing no defects will allow more energy to pass through than one containing defects. Air is used as couplant between the transducers and the part under examination. High sound pressures are therefore necessary to compensate losses due to the impedance difference between air and material.

MX Omniscan (OLYMPUS) with Phased Array probes and different encoders, and 007CX AIRSCAN from QMI together with SONIA and Inspect View software (TECNATOM) have been utilized for conventional and air coupled UT testing, respectively.

3. Results

3.1 NDT sample evaluation

Figure 2 shows the obtained inspection results from CFRP representative sample (extracted from cabin bottom) with the main recorded indications within the different samples and cockpit inspections. Several indications are tracked and indicated as A-E for fiber gaps (from Fiber Placement manufacturing process); and F-G for areas showing lack of resin (macro porosity). Fig. 2.e shows the representation of tomographic cross section for characterization of the defectology. The highest detectability is achieved by active thermography and conventional ultrasonics (Fig. 2.a and c, respectively), whiles laser shearography (Fig. 2.b) is only capable of tracking the main horizontal fiber gaps. A good detectability is also observed by air coupled UT (Fig. 2.d) with the lack of some indications.

These results agree with the one obtained in the different inspections, which are not presented in this work from simplification.

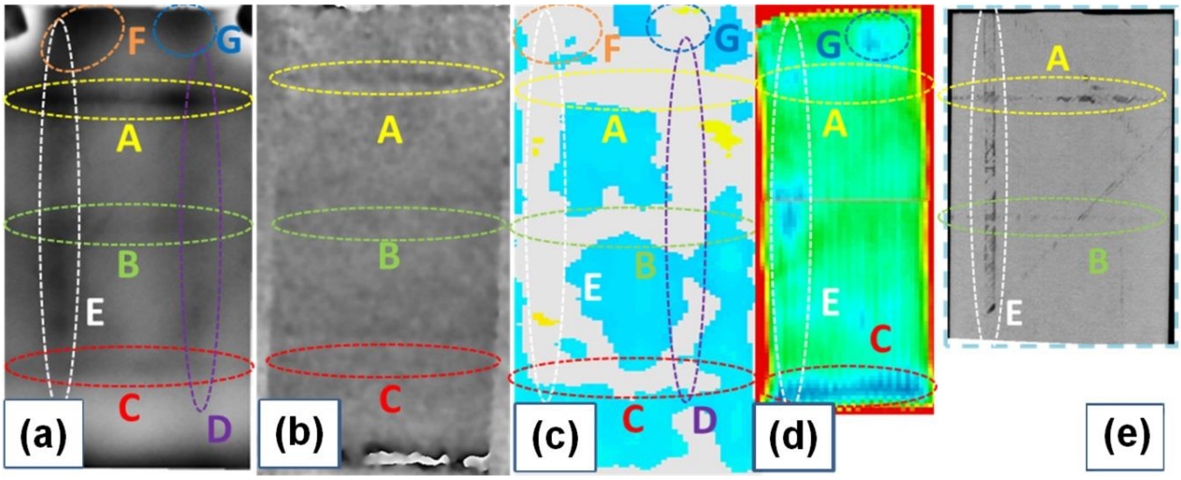

Fig. 2. Inspection results for the different NDT methods under evalution for damage monitoring system: (a) Active thermography; (b) Laser Shearography; (c) Conventional and (d) Air coupled ultrasonics; and (e) Computed tomography cross section for sample evaluation.

After selection of the most promising technique, different inspections have been performed on two CFRP panels in order to address the foreseen on-line inspection strategies: (i) continuous monitoring during mechanical loading (static/fatigue) of the cockpit using passive thermography; and (ii) Scheduled/Non-scheduled inspections by active thermography during mechanical test stops (no loading). The panel was subjected to compression loading on CAI (Compression After Impact) test rig. Previously, a 30 J impact was performed.

Figure 3 shows the timing graph of the subtracted normalized temperature along the whole loading cycle (up to failure @ 78kN). All observed peaks correspond to fiber breakages and showing as well evolution of the delamination (caused by previous impact) at the high loads (from 60 kN). The magnitude of the peak is directly related with the amount of the generated heat, and therefore with the severity of the appearing damage. The five largest peaks are depicted in the timing graph and related with passive thermographs from Figure 4.

3.2 IRT continuous monitoring and schedules inspections

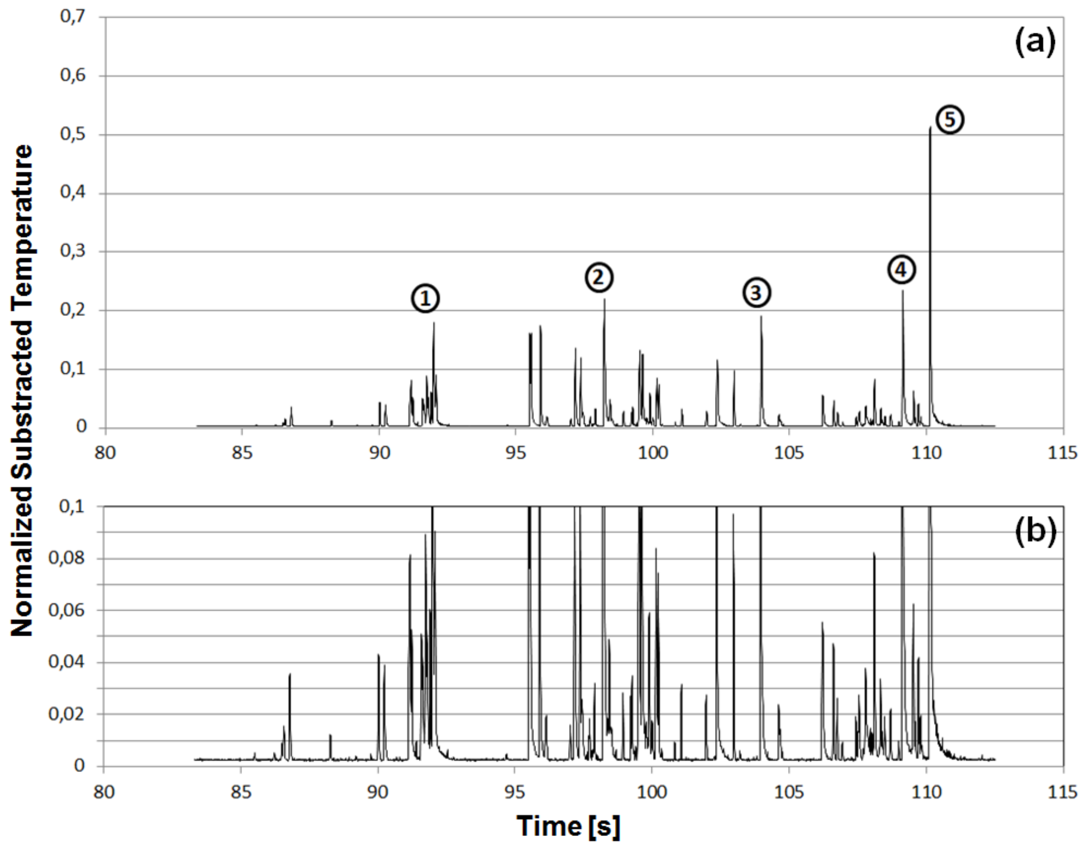

Fig. 3. Normalized substracted temperature (NST)/Timing graph (a) highlighting the 5 main (largest) indications; and (b) magnified low scale NST (from 0 to 0.1) for observation of all recorded peaks related to damage apparition. Note: Normalized substracted temperature is calculated from raw thermographs by using processing algorithms [3,8].

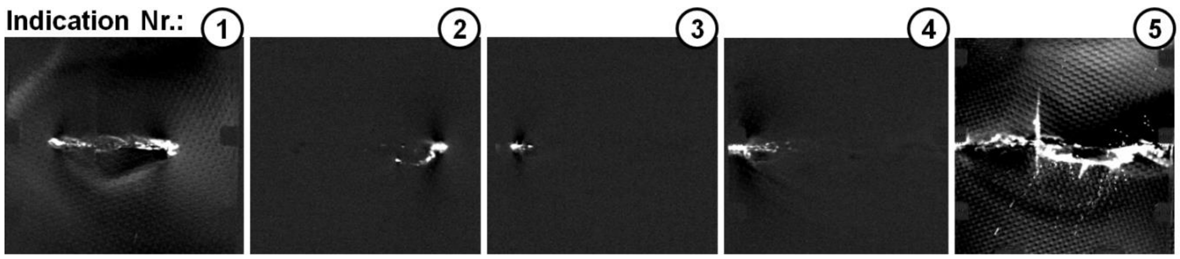

Fig. 4. Passive thermographs obtained from main indication (1 to 5) after image processing (Normalized subtracted temperature).

Figure 5 shows the results obtained through Active IRT and UT (for comparison issues) before testing and after failure. In all cases, the temperature increment produced during the thermal excitation was below 5˚C. A good correlation is observed from thermographic and ultrasonic inspections.

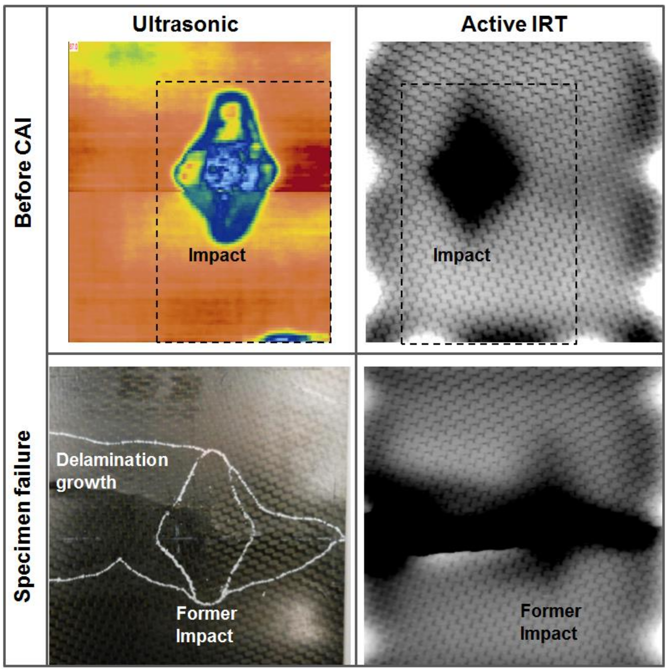

Fig. 5. UT and Active IRT results before and after CAI testing (specimen failure).

4. Discussion

Tables 1 and 2 show the summarized characteristics and inspection detectability of the different NDT methods. Within the required inspection characteristics, thermography, air coupled ultrasonic and laser shearography comply with the most requirements, being non-contact and with low cost inspection set-ups. Only thermography and laser shearography can perform fast inspections which make them suitable of in-live monitoring. On the other hand, LS can be sensitive to vibration decreasing the detectability method. For the case of IRT, a wide variety of infrared cameras is available, and with different sensitivity to cost ratios. The last can be adjusted for finding the most cost effective solution. IRT also shows as the most promising technique for being applied during the execution of a mechanical fatigue test (together with air coupled ultrasonics but with very limited inspection speed, accessibility, and only capable of providing local information in a very small area).

Table 1. NDT methods characteristics selection chart.

	Non-contact	Fast Inspection	Applicable during fatigue testing	Scheduled Inspection	Low cost equipment	Low cost set-up
IRT	✓	✓	✓	✓	✓	✓
LS	✓	✓		✓		✓
Conventional UT				✓	✓	
Air coupled UT	✓		✓(*)	✓	✓	✓

(*) very limited

Conventional and air coupled ultrasonics registers have the best performance in terms of detectability. Unfortunately, the requirement of contact can limit the technique for in-live monitoring of composite structured subjected to fatigue testing, together with a reduced inspection speed. All considered methods can be applied effectively in sandwich and monolithic constructions (with the exception of LS for the last one). Contrarily to ultrasonics, IRT and LS could not estimate (quantitatively) the position of the flaws within part thickness. Also, both techniques are limited for the detection of porosity. Taking into account that such defectology could appear only during manufacturing, this issue cannot be considered critical for on-line monitoring during mechanical testing and/or detection of damage apparition.

Finally, infrared thermography shows as the most suitable candidate for developing the NDT system for progress damage monitoring. Due to the possibility of performing easy inspection set-ups, the advantage of non-contact and reduced inspection times, infrared thermography will allow the evaluation of large areas in very short processing times. Also the technique could perform live monitoring inspections unfeasible for other NDT techniques under evaluation, and suitable for the detection of damage apparition and evaluation of its evolution.

Table 2. Defects detectability for the NDT methods considered.

	Delaminations/ debondings	**Level of porosity**	**Impact damage**	**Cracks**	**Flaw position along thickness**	**Monolithic**	**Sandwich**
IRT	✓		✓	✓		✓	✓
LS	✓		✓	✓			✓
Conventional UT	✓	✓	✓	✓	✓(*)	✓	✓
Air coupled UT	✓	✓	✓	✓	✓(*)	✓	✓

(*) not available in through transmission mode

5. On-line Monitoring Strategy

The continuous monitoring of CFRP cockpit consists on the main task for the acquisition system (see use-case in Figure 6). This must be performed in the real-time controller plug-in. The acquisition system includes the IRT camera(s) plug-in to capture a live feedback from the camera and processes the images (from passive IRT inspections) as they are being recorded using a light-weighted algorithm (with the methods provided by the image processing plug-in).

Once the user selects the monitoring locations (according to stablished inspection parameters), the system provides a monitoring instruction and the acquisition starts. The data is evaluated in real-time and once a discontinuity is detected (e.g. indication fiber crack by heat creation) an alarm message is provided to the user. Then, the recording of specific data within a selected time window is performed. According to the severity of the indication, the user can select to perform a non-scheduled inspection on the specific region of interest (in this case using active IRT). By means of specific software developed for the project, a complete analysis of the indication can be performed and compared with previous information of the desired area, in order to track the evolution of the defect. Finally, the user has the possibility of continue with the testing once the evaluation is performed.

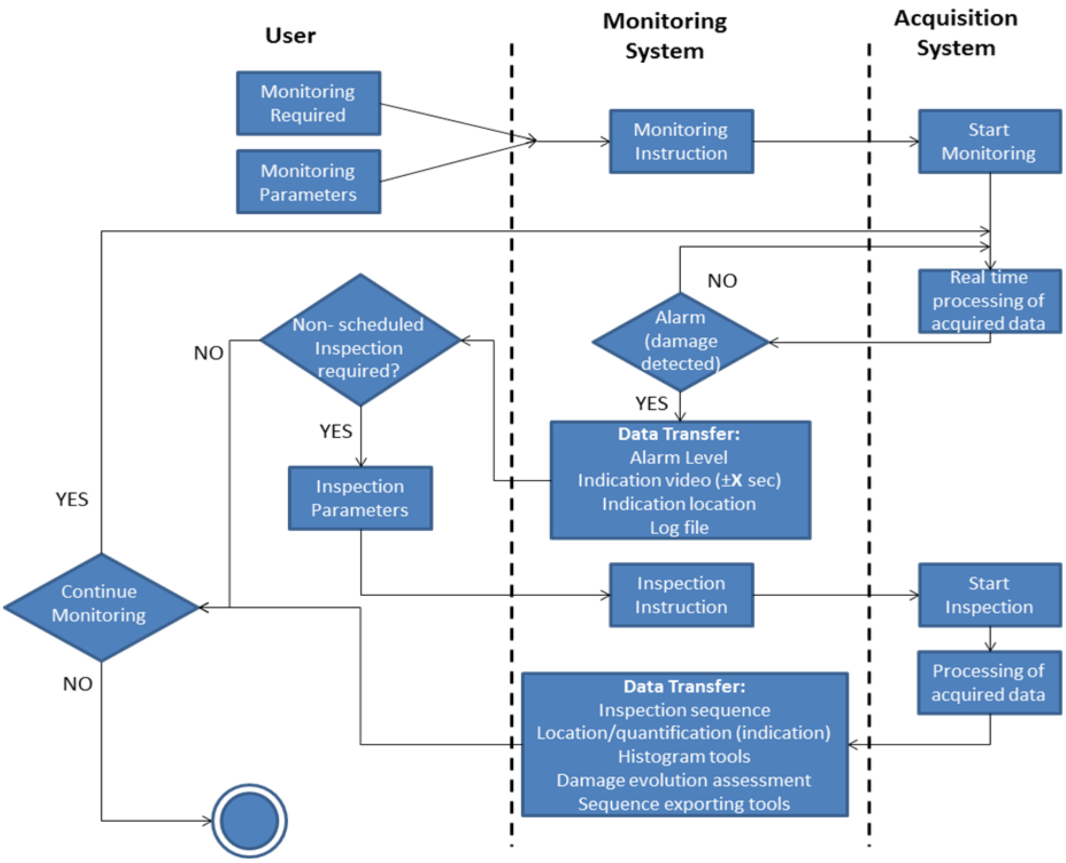

Fig. 6. Use case for continuous monitoring.

6. Conclusions

A feasibility study for selection of most suitable NDT method for on-line mechanical testing monitoring has been performed. Infrared thermography shows as the most suitable candidate, capable for detecting the all required indications during testing. The set up will consist in performing passive inspections for damage detection during static/fatigue testing, and use the active mode for scheduled and non-scheduled inspections. The last will be applied for quantifying the damage area (e.g. delamination growth) in order to perform a comparative analysis against the whole specimen life.

Views of the target specimen, testing rig and an active thermograph (showing structural information from omega stiffeners and two indications related to skin delaminations) for CFRP cockpit is presented in Figure 7. The IRT system is being developed for tracking different positions on the cabin structure. These locations are related to the different induced flaws (mainly impact damage). The system will implement motion strategies in order to increase inspection resolution. This will also be employed for displacing the camera during active inspections for scheduled and non-scheduled events.

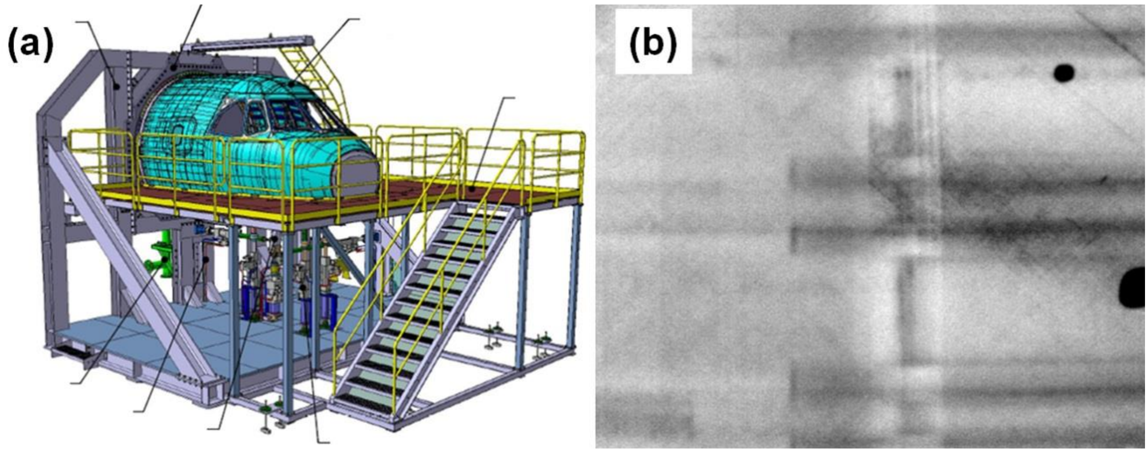

Fig. 7. (a) View of testing rig for CFRP cabin; and (b) active thermograph showing structural information and indications related to skin delaminations (black spots).

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References

[1] A. Zorrilla, M.L. Santamaria, P. Dominguez, F. Lasagni: A Comparative Study for Defect Detection in CFRP Composite Materials by Active Thermography and US phased array, Proceedings of the 16th International Conference on Composite Structures (ICCS16), 28-30th June, Oporto, Portugal, 2011.

[2] Y.Y. Hung, Y.S. Chen, S.P. Ng, L. Liu, Y.H. Huang, B.L. Luk, R.W.L. Ip, C.M.L. Wu and P.S. Chung: Review and Comparison of Shearography and Active Thermography for Nondestructive Evaluation; Materials Science and Engineering, Vol. 64 (2009) 73-112.

[3] B. Rodríguez, C. Galleguillos, R. Fernández, F. Lasagni. Passive Infrared Thermography for Damage Monitoring during Structural Testing of CFRP Parts, in proceedings 16th European Conference on Composite Materials, Seville 2014.

[4] C. Galleguillos, P. Ruiz, E. García, D. Jiménez, P. Arroyo, F. Lasagni: Non-Destructive and Contactless Evaluation of Sandwich Structure using Laser Shearography (Evaluación no destructiva y sin contacto de elemento sándwich aluminio/foam por Laser Shearography), Proceedings 13º Congreso Nacional de Ensayos No Destructivos, 6-7 May, Seville, Spain, 2015.

[5] M.L. Santamaria, E. Pagnoux-Lacaze, P. Arroyo-Perfumo, J.M. Gallardo, F. Lasagni: Estudio de Inspección Ultrasónica en Laminados Curvos y Radios en CFRP, Journal of the Spanish Association for NDT (AEND), 58, 2012, 34-40.

[6] M. A. Nieto, Z. Re, E. Cuevas: TTU Phased Array: Quality and Productivity; 6th International Symposium for NDT in Aerospace, Madrid (2014).

[7] E. Cuevas, C. García, C. de Miguel-Giraldo, M. Mora: Online NDI concept for composite manufacturing process and approximations for the NDT of CFRP Materials Prior to the Autoclave Curing Process; 6th International Symposium for NDT in Aerospace, Madrid (2014).

[8] J.-M Roche, D. Balageas, B. Lamboul, G. Bai, F. Passilly, A. Mavel, G. Grail, Passive & active thermography for in situ damage monitoring in woven composites during mechanical testing, in Proceedings Quantitative Non Destructive Evaluation Conference, Denver, 2012.