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Non-Destructive Testing for Detection, Localization and Quantification of Damage on Composite Structures for Composite Repair Applications

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Abstract. Composite materials are being widely used for manufacturing aircraft components due to their superior material properties such as high strength, light weight, corrosion resistance, etc. However, compared to isotropic materials, composite materials exhibit complex damage characteristics. Moreover, when the composite material is impacted by a foreign object they are prone to barely visible impact damages such as delamination, matrix cracking, etc. Since composite materials are being increasingly used in aircraft component production the likelihood of composite damage occurrence during aircraft operation increases as well. Therefore, it is crucial to address the challenges associated with detecting composite damage and performing composite repairs. The focus of this research is the development of automated depot repair technology for composite structures, which combines; non-destructive testing (NDT) for damage size determination, damage removal by milling, repair by adhesive bonding of a repair patch and NDT for post repair assessment. In this study, a damaged curved CFRP panel with dimensions of 1.3 × 1.3 m was used for the development of algorithms for automated composite repair process. NDT using a laser line scanner was performed to acquire the composite panel's surface data, to assess features of the panel such as its shape, visible damage, etc., and the thermographic inspection was done to assess the extent and location of internal damage. Algorithms were developed to perform data fusion of the sensor data; a) to detect, localize, quantify and visualize the damage on the composite panel, through analysis of gradient changes between defined local sections of the panel, b) to generate a 3D model of the repair region based on the surface geometry and with design considerations that ensures the optimal structural integrity of the repaired panel, and c) to output suitable computer-aided design (CAD) files which can be imported to the milling tool, to perform the damage removal, and the CAD tool, to fabricate the repair patch. Finally, after the composite panel undergoes the milling and repair process, NDT inspections will be performed to ensure its safety and integrity.

Keywords: automated composite repair, NDT, laser line scanner, thermography.

1. Introduction

Aircraft structure damage can occur during flight or on the ground. Common causes are human error, impact from runway debris and bird strike. As the number of aircraft in operation has been increasing significantly [1], the frequency of aircraft structural damage event can also be expected to increase. Operational costs due to grounded aircraft can be significantly high; Ball et al reported that in the year 2007 fight delay cost airlines an estimated $32.9 billion [2]. As a result, an automated system capable of inspecting damage and for repairing damage to enable the earliest return of the aircraft to service can lead to large cost savings. The realization of an autonomous system capable of damage assessment for on-site repair involves considerable development of tools and algorithms for performing the desired on-site inspection and providing accurate data as input to the repair process.

The composite repair process involves damage assessment, which can be performed using several different types of sensors and non-destructive techniques (NDT), such as PZT sensors [3], shearography [4], phased arrays ultrasonic testing [5], thermography [6] and laser scanning [7] for inspecting visual and barely visible impact damages on composite structures [8]. Furthermore, a multi-sensor environment consisting of various NDT techniques can be used for obtaining data for feature extraction and then the use of data fusion [9] to yield accurate results for damage monitoring and diagnosis on aircraft structures. When a damage is detected on the composite structure, it can be repaired using the scarfing repair approach which involves removal of the damage region by machining the composite layers [10] and, subsequently, the repair can be completed by bonding the patch to the parent structure [11].

When an aircraft structure is damaged, an automated system that can inspect the damage to determine the extent of the damage, output the area that needs to be removed to repair the damage, perform repair and subsequently assess the repair is highly desired. Therefore, the topics covered in this paper include structural inspection using multiple NDT techniques, data fusion and analysis, and damage removal. The structure of the paper is as follows: a) in Section 2, the methodology, experimental set-ups and the algorithms developed to analyze the data acquired using the line-laser scanner and thermography inspection to automate the damage detection, localization and cut-out profile for damage removal is presented, b) in Section 3, the damage localization results and the cut-out profile model generated by the algorithms are presented, and c) the conclusions and future works are presented in Section 4.

2. Methodology

The methodology of the automated damage assessment and repair system involves inspection of the structure using multiple NDTs. After the data acquisition process, data fusion is done in order to perform damage analysis as consistently and accurately as possible. The data fusion and analysis will determine if any damage exists and if damage is detected then it will localize and quantify the damage on the structure. Subsequently, the file containing the damage parameter will be output so that the damage repair process can be performed. The damage repair process involves the damage removal and patch fabrication using the damage parameters provided by the damage analysis algorithm. After the damage removal is performed the patch will be bonded to the parent panel. Finally, the repaired structure will be accessed using the NDT. The automated damage assessment and repair methodology is presented in Fig. 1.

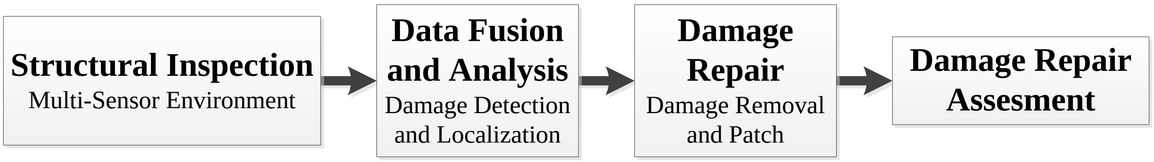

Fig. 1. Functions of automated damage assessment and repair system.

In this paper, the main research area focus is on the development of algorithms for data fusion and for the damage analysis process capable of assessing the data acquired by multiple NDTs used for the structural inspection. Moreover, the NDT techniques selection criteria for the data acquisition includes; 1) a suitable method for determining the structural geometry and damage information to create the cut-out profile for damage removal application and patch profile for patch fabrication process, and 2) an additional portable light-weight NDT technique for damage analysis in order to increase the consistency and accuracy of the damage analysis tool. The output provided by the algorithms will then be used for performing the damage removal. The experimental set-up and the damage detection and localization algorithms are presented in the following subsections.

2.1 Experimental Setup

The damaged curved CFRP panel, with dimensions of 1.3 × 1.3 × 0.0038 m and a radius of 2 m, was inspected using a laser line scanner and thermographic inspection. The laser line scanner was used to determine the composite panel's surface features such as its geometry and damage on the panel. A high-speed laser line scanner, Micro-Epsilon scanControl 2950-25, which has 2 μm z-axis resolution was fixed on the end of the arm of the Kuka robot, Kuka KR210, to scan the CFRP panel. The scan path was assigned by selecting reference points with respect to the panel's curvature to create the curved scan line path, to scan the entire CFRP panel. Subsequently, the KUKA robot arm's 3D position and angle on the scan path was determined to ensure that the laser line scanner was positioned normal to the surface of the CFRP panel, and the geometry of the CFRP panel was determined in the coordinate system of the manufacturing cell. The set-up for the line laser scan of the CFRP panel is shown in Fig. 2. The laser line scanner stores the acquired data in point cloud data (PCD) format, which consists of the x, y and z coordinates of each point scanned by the laser scanner. The PCD with coordinates of about 39.6 million points on the panel were acquired and stored for further processing.

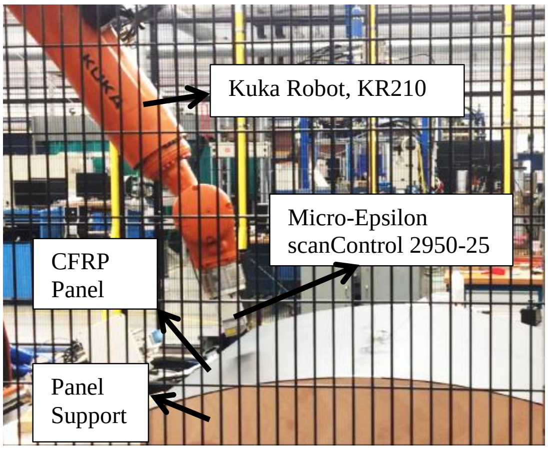

Fig. 2. CFRP panel scanning using the laser line scanner.

The PCD acquired using the laser line scanner provides the surface level information. Therefore, it is essential for determining the geometry of the structure and any defects on the surfaces. A portable thermography device, NDTherm NT (OPGAL), was used to determine the extent of the internal damage by TiaT Europe at TU Delft. As shown in Fig. 3, the infrared images were acquired using the NDTherm NT (OPGAL) placed on top of the region with visible damage of the CFRP panel.

The data acquired using the laser line scanner and the thermographic inspection were analyzed using the automated damage localization and quantification algorithms, developed at TU Delft (see Section 2.2), to determine the damaged area and to model the profile for damage removal. Finally, the output parameters from the algorithm were used as input parameters for the damage removal using the portable high precision 5 axis milling machine, MobileBlock device, provided by DMG MORI SAUER Ultrasonics GmbH. In order to perform the damage removal from the CFRP panel, the MobileBlock was placed on top of the CFRP panel and locked to the panel using the suction legs. The experimental set-up for the damage removal process is shown in Fig. 4.

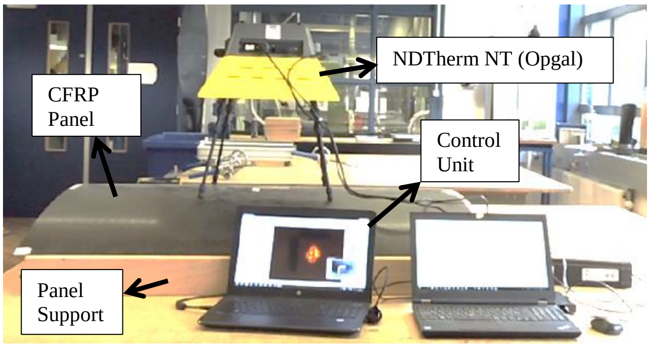

Fig. 3. CFRP panel inspection using the NDTherm NT (OPGAL).

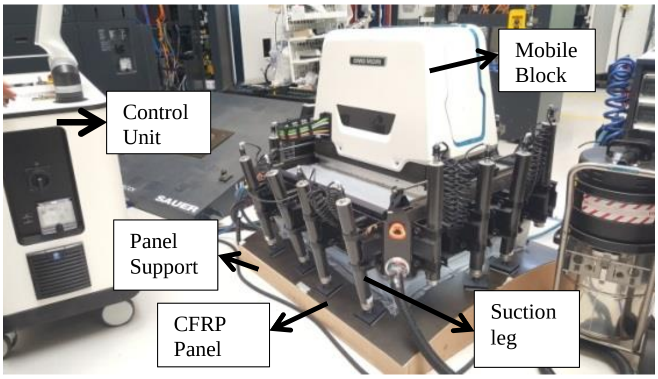

Fig. 4. Damage area removal using the MobileBlock.

2.2 Algorithm overview

The data acquired after the structural inspection was imported to the automated damage detection and localization algorithm for; 1) data pre-processing of the laser line scanner PCD data and infrared image, 2) damage detection and quantification and 3) providing the geometry and location of the scarf repair as input to the milling process. An overview of the algorithm is illustrated in Fig. 5. The first step of the algorithm involves pre-processing of the data acquired using the laser line scanner and thermographic inspection, in which; 1) the algorithm determines the geometry information of the curved CFRP panel based on the data acquired using the laser line scanner, 2) the panel's geometry data is used to reconstruct the 3D model of the curved CFRP panel, and 3) subsequently, the reconstructed model of the CFRP panel is then used to transform the pixel information of the infrared image to the coordinate system of the PCD of the CFRP panel obtained by the laser line scanner.

The laser line scanner and infrared image PCDs were analyzed independently to determine the damaged area. The damage length on the PCD obtained using the laser line scanner was determined by analyzing the gradient change in the z-axis by scanning the PCD in the x-direction and y-direction at x-interval and y-interval, respectively. The infrared image analysis for damage determination was also done by analyzing the pixel data by scanning the PCD in the x-direction and y-direction at specified intervals. After the damage localization procedure, the damaged areas are enclosed using an ellipse, which is created using the minimum and maximum x-values and y-values of the damage region. The ellipse covering the damaged area of the laser line scanner PCD and the infrared image PCD are compared to check if they are in agreement.

Finally, the damage region determined based on the results obtained from the laser line scanner and thermography image analysis is used for modeling the cut-out for milling the CFRP panel. The cut-out profile is modeled so that the size of the ellipse at the bottom of the panel is 15 mm apart from the detected damage. Additionally, a commonly used scarf ratio [12], 1:20, was selected for modeling the cut-out profile for bonded repair applications. Finally, the milling profile parameters are output in .stl format by the algorithm. In the last step, the output parameters of the scarf profile are used as an input for damage removal using the MobileBlock.

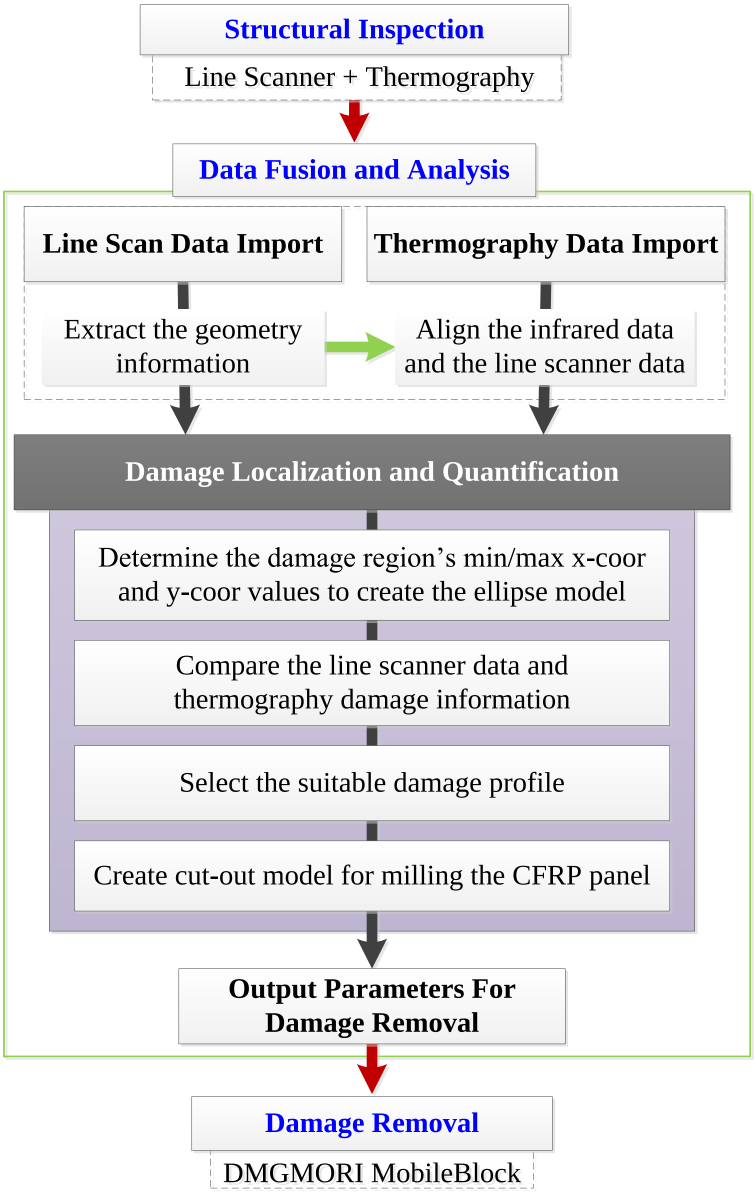

Fig. 5. Overview of the damage detection and localization algorithm.

3. Results

The PCD acquired after the entire panel was scanned using the laser line scanner is presented in Fig. 6 (a). The damage information on the PCD is represented by deviations in the z-value and missing point cloud elements, as shown in Fig. 6 (b). The infrared image acquired through the thermographic inspection is presented in Fig. 7. The white and the black regions, corresponding to hottest and coldest region, can be seen on the infrared image because of the uneven distribution of temperature due to the presence of the damage. These two data sets were imported to the automated damage localization and quantification algorithms for further analysis.

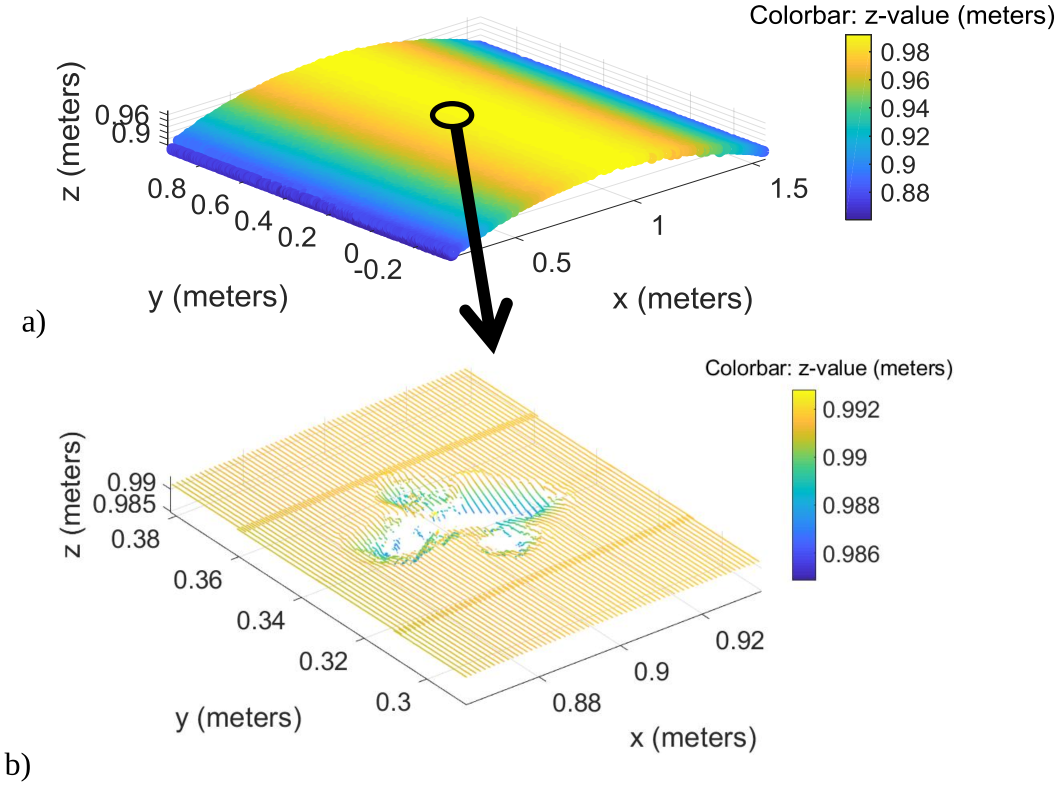

Fig. 6. a) Visualization of the PCD of the entire CFRP panel acquired by the laser line scanner and b) close-up of the damage region.

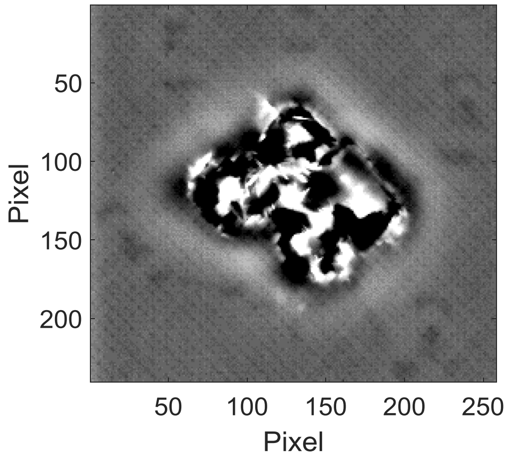

Fig. 7. Infrared image acquired using the NDTherm NT (OPGAL).

The damage localization algorithm was used to determine the damage location and size by analyzing the laser line scanner data and the infrared image. In case of the laser line scanner, the algorithm analyzed the PCD that lie between x-values of 0.7505 m and 1.049 m, and y-values of 0.24 m and 0.44 m. Whereas, the data range analysis for the infrared image was performed for: x-values between 0.8473 m and 0.9459 m, and y-values between 0.2977 m and 0.3794 m. Fig. 8 (a) shows the damage region, with a maximum x-length of 48.9 mm and a maximum y-length of 41.1 mm, detected by analyzing the PCD obtained from the laser line scanner. The algorithm then performed the conversion of the pixel information obtained using the thermographic inspection to PCD information with respect to the laser line scanner PCD information, as shown in Fig. 8 (b). In Fig. 8 (c), the damage region detected by analyzing the infrared image is compared with the results obtained by analyzing the laser line scanner data. Moreover, it can be seen that the thermographic inspection detects a larger damage area than the laser line scanner, as the damage detection algorithm determines the damage to be 22.4 mm and 12.3 mm longer in the x and y-directions, respectively.

Furthermore, since the damage location detected and quantified by these two different NDT techniques overlaps with each other, the certainty of the detected damage location is increased. As a result, based on the damage information determined by the algorithm the maximum damage length in the x-direction and y-direction is selected to model the cut-out profile for damage removal, as shown in Fig. 8 (d): with ellipses of maximum x-length of 253.2 mm at the top surface and 101.6 mm at the bottom surface of the panel, and maximum y-length of 235.4 mm and 83.8 mm at the top and bottom surface, respectively. The parameters output by the algorithm was then used for the damage area removal as shown in Fig. 9.

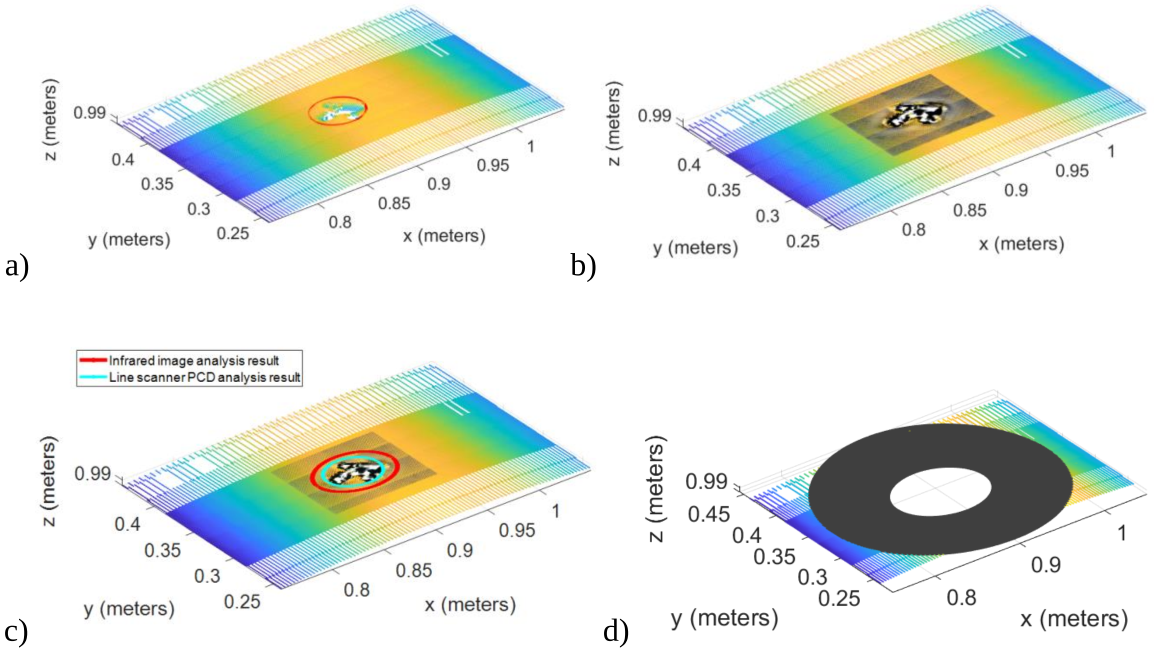

Fig. 8. a) Damage region detected by analyzing the laser line scanner PCD, b) infrared image processed and converted to the laser line scanner PCD coordinate system, c) infrared image and laser line scanner based damage region comparison and d) cut-out profile model generated by the algorithm.

Fig. 9. Damage removed using the MobileBlock.

4. Conclusions and Future Works

In this paper, the algorithms developed for processing PCD and infrared images for automated damage detection and localization was presented. The developed algorithm was used to detect, localize, quantify, visualize the damage, and to output the cut-out profile parameters to the milling machine. Moreover, the presented work covers the composite structure monitoring, data analysis, and damage removal tasks. The subsequent tasks in the project; inspection of the damage removal performed by the MobileBlock, composite repair by bonding the patch to the CFRP panel and repair assessments remains to be performed to determine the suitability of the performed repair work. Furthermore, the developed algorithm needs to be further tested for performing the automated repair works in order to realize a fully automated repair system.

Acknowledgements

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