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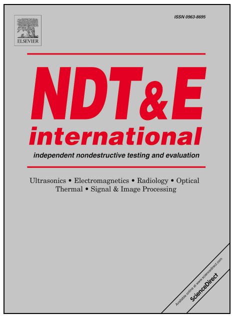

Surface damage evaluation of honeycomb sandwich aircraft panels using 3D scanning technology

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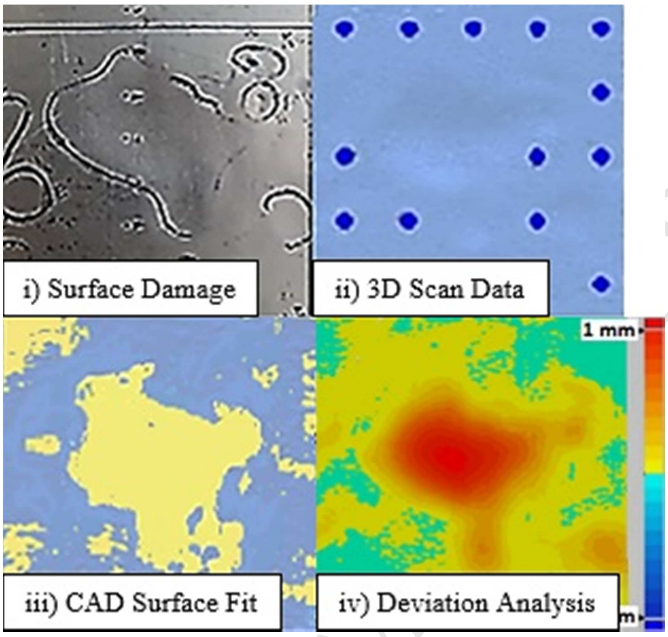
Graphical abstract:



Surface Damage Evaluation of Honeycomb Sandwich Aircraft Panels Using 3D Scanning Technology

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Keywords: *3D scanning, surface damage inspection, dent, honeycomb sandwich structures, non-destructive evaluation (NDE)*

Abstract

A 3D scanning method is proposed for the measurement of surface damage on aircraft structural panels. Dent depth measurements were shown to be within 0.04 ± 0.06 mm (95%) of those taken using a Starrett 643J dial depth gauge based on 54 flat panel dents, and 0.04 ± 0.05 mm (95%) based on 74 curved panel dents. Dent depths were quantified by the difference between a point cloud rendering of the damaged surface and a surface fit approximating the original, undamaged surface. Convergence studies were used to evaluate the accuracy of the surface fit, enabling this technique to be used as a stand-alone inspection method. Image processing was used to measure dent length and area, and the results showed that this method is more efficient and reliable compared to manual methods. This novel non-destructive evaluation technique thus demonstrates potential to enable the timely extraction of surface dent measurements during on-site aircraft inspections.

1. Introduction

Honeycomb sandwich panels are used extensively in both commercial and military aircraft due to their high stiffness- and strength-to-weight ratios. Honeycomb panels are constructed using thin face sheets bonded to a low-density hexagonal core. For aluminum-faced panels, impact due to hail or tool drop can result in both surface denting, as shown in Figure 2, and buckled honeycomb core, which may reduce residual strength and compromise structural integrity [1]. Dent limits for aircraft panels are usually defined in the aircraft standard repair manual (SRM), which is provided by the original equipment manufacturer (OEM).

OEM damage limits are typically defined in terms of the structural criticality of the affected panel; dent depth and length; total dent area; and the proximity of dents to specific features. Dent depth is usually measured using a dial or digital depth gauge [2-9], a ruler, or, in some cases, a high resolution electronic indicator [10, 11]. For the dial depth gauge, the gauge is positioned with the needle pointing normal to the inspection surface, and the dent is probed by taking multiple manual readings within the dent impression to find a maximum value. This can be time-consuming for the manual inspection of surfaces with many dents, such as aircraft panels exposed to hail damage or tool drop. This process is further prolonged by the manual recording of each measurement when using a dial depth gauge, like the one shown in Figure 1 used within this study.

Figure 1: Starrett 643J dial depth gauge

Dent area is usually conservatively approximated as a circle with the longest length of the dent being used as the diameter. A disadvantage of these methods is that measurements are subject to interpretation and variation based on inspection personnel. Manual measurements may also require repetition to confirm observations. A method introduced for automotive applications involves high accuracy electrical sensing to measure dent depth [12, 13], but the approach is limited in portability and so has limited application for in-service aircraft inspection. There is thus a need for quick and reliable methods of assessing surface damage on aircraft components. The current study presents a novel application of 3D laser scanning technology for the semi-automated inspection of surface damage on in-service honeycomb sandwich aircraft panels.

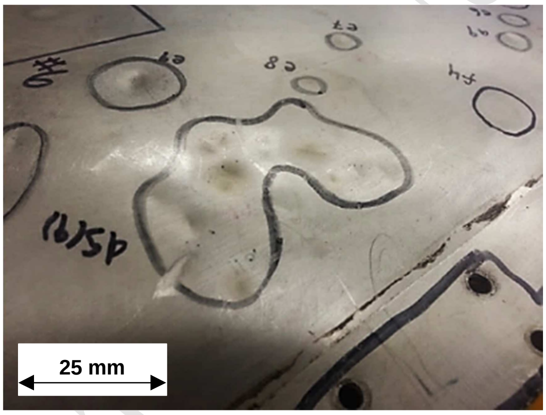

Figure 2: Dent cluster on a retired aircraft panel with dents circled using black marker by inspection personnel

3D laser scanning is a method used to collect spatial data from real-world objects. A point cloud of geometric data corresponding to the surface of the scanned object is obtained using optical technology. In the last few decades, 3D laser scanning has become increasingly important for quality control in the manufacturing industry [14], and plays a key role in the inspection of complex assemblies in many industrial applications. 3D scanning systems such as the FARO® Edge direct laser light on an object while exploiting a camera to look for the location of the laser dot. The laser dot, camera, and laser emitter form a triangle, and known lengths and angles are used to determine the location of the laser dot. This 3D scanning technique is the basis for the methodology developed in this study.

3D scanning represents an improvement over traditional coordinate measurement machine (CMM)-based methods for many inspection processes. One reason is its non-invasive nature, which is attractive compared to systems that require probe-to-specimen contact during inspection. In addition, 3D scanning methods usually do not require physical alignment of each inspection piece like many CMM-based systems because the point cloud rendering of the part can be oriented digitally. There are many examples of 3D laser scanning technologies being used to digitize objects for engineering and scientific applications. These applications are primarily categorized by the use that is made of the point cloud data following the laser scanning process. Four major applications are digitization, reverse engineering, quality assurance and non-destructive evaluation (NDE).

Digitization involves the compilation of 3D scan data to preserve geometric information pertaining to real-world objects. Examples include the digitization of cultural artifacts [15-18], and the digitization of large, fragile statues under non-laboratory conditions [19, 20]. In human engineering, 3D scanning has been used to extract and compile anthropometric data to be used for apparel sizing, protective equipment design, and workstation layout [21]. Additional examples include industrial, historical, medical, and criminal investigation applications [22].

Reverse engineering applications are characterized by the use of 3D scan data to develop CAD models corresponding to real-world geometries. In many cases, the reverse engineering process is faster and more accurate than developing models based on measurements made using manual techniques [23]. This process is also convenient when documentation is lacking, or when the part configuration has changed from the initial design. Reverse engineering based on 3D laser scan data has been investigated for automotive applications such as the re-manufacture of a sheet metal cutting die [23] and for the potential benefits offered to engineering design and production processes [24].

Quality assurance inspection processes differ from reverse engineering in that CAD models for the object are available and represent the manufacturing standard for the component being inspected [25]. Scanning technologies are used to compare the component to the standard and ensure that design tolerances are respected. This procedure is common in the aerospace and medical industries, where even the smallest defects may be unacceptable [26]. A typical application is the measurement of surface roughness and waviness, as well as the gauging of 3D topology of machined surfaces [22]. The usefulness of 3D scanning has also been demonstrated for the characterization of drilling tools, whose complex geometry makes conformity inspection challenging [14]. Another study was conducted in Reference [23], which compared point cloud data of the sheet metal cutting die to a CAD model of the part for inspection purposes.

The use of 3D laser scanning for NDE and surface inspection is less common and can involve recognizing surface damage by geometric features, or comparisons between images of damaged and undamaged geometry. Applications in civil engineering include defect detection in concrete tunnel liners [28], surface damage recognition in concrete structures [29], and the inspection of concrete layer pull-off adhesion [30] and underbridge geometries [31]. Surface inspection has also been performed using laser scanning to evaluate surface roughness via confocal laser scanning microscopy (CLSM) [32], survey river bed topology [33], and inspect open-pit mining rights [34]. Creaform Inc., a company specializing in 3D scanning-based NDE solutions, provides a surface damage inspection system primarily marketed for pipeline assessment [35], which compares a scan of the pipe surface to a cylindrical surface. There have not been the same applications in the aerospace industry, which continues to rely on manual measurements and visual identification of surface damage. 3D laser scanning represents a portable alternative for the inspection of surface damage for honeycomb aircraft structures, but presents a challenge because the original geometry of the part is unknown to the inspection personal and must be recreated using the geometry of the damaged part.

In the current study, a method is proposed for measuring the depth, length and area of dents in aircraft panels by comparing point cloud data from the in-service, damaged part with a CAD surface approximating the original, undamaged geometry of the part. Quantifying the deviation between the original and damaged geometries results in a measurement of dent depth, whereas dent length and area are evaluated using image processing techniques. During regular inspections, damage must be identified as being negligible, allowable or unacceptable based on these measurements, and the proposed method has the potential to be a more reliable and accurate non-destructive inspection tool than what is currently used in the aerospace industry. The novelty of this method lies in the fact that it can recreate models of both the damaged and undamaged parts without any pre-existing CAD information. This is significant because access to the undamaged version of a component is often not possible within the aerospace industry. Without access to the undamaged part, evaluation of the accuracy of the recreated surface is challenging, and this is addressed in the current study through the development of a convergence technique. This method demonstrates potential for application in any field requiring non-destructive evaluation of surface damage, and represents a semi-automated inspection solution, which may be used to replace time-consuming and less accurate manual processes.

2. Materials and Methods

The proposed 3D scanning-based inspection method was developed and validated using three honeycomb sandwich aircraft panels that had been retired based on collective surface damage due to low-velocity impact that exceeded the allowable damage limits defined in the aircraft SRMs. The three specimens included two approximately flat panels with specifications as listed in Table 1, and a curved panel with specifications as listed in Table 2. Photographs of one of the flat panels and the curved panel are shown in Figure 3.

Table 1: Flat panel specifications

Specification	Value
Top face sheet material	Al 7075-T6
Core material	Al 5052
Bottom face sheet material	Epoxy/fiberglass
Adhesive	Heat-resistant epoxy Hysol® EA 934NA
Total panel thickness	12.7 mm (0.50 in)
Top face sheet thickness	0.51 mm (0.020 in)

Table 2: Curved panel specifications

Specification	Value
Top face sheet material	Al 2024-T3
Core material	Al 5052
Bottom face sheet material	Al 2024-T3
Adhesive	Heat-resistant epoxy Hysol® EA 934NA
Total panel thickness	6.91 mm (0.272 in)
Top face sheet thickness	0.51 mm (0.020 in)

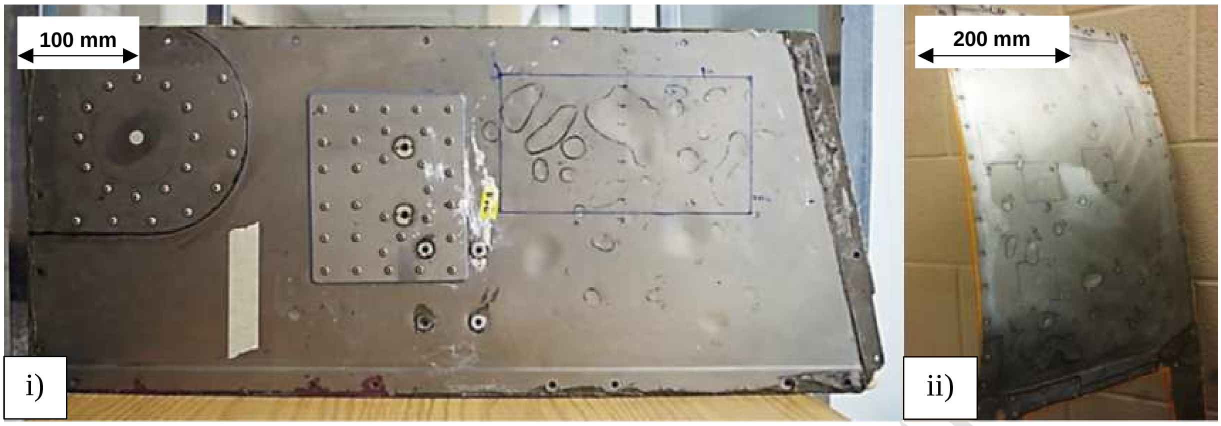

Figure 3: Honeycomb sandwich aircraft panel inspection specimens. i) flat panel, ii) curved panel

An outline of the methodology is given below, and is illustrated in Figure 4:

1. The panel is scanned to produce a point cloud rendering of the damaged surface.
2. A grid of circular point cloud regions corresponding to the undamaged surface of the panel is selected as shown in Figure 4 ii), whereas any region identified as being within a dent is manually omitted.
3. A 3D CAD surface is fit to the grid of undamaged regions to recreate the geometry of the undamaged panel, as shown by the yellow surface fit through the point cloud data in Figure 4 iii). The accuracy of the surface fit is evaluated using a convergence study as discussed in Sections 2.2.1-2.2.2.
4. A deviation analysis is performed between the point cloud data from the damaged panel and the 3D CAD surface representing the undamaged panel, producing a color map that identifies the dents as shown in Figure 4 iv).
5. Dent depth information is obtained by probing for the maximum dent depth value within the color map generated in Step 4.

6. Image processing techniques are applied to the color map using a minimum dent depth value to measure dent length and area.

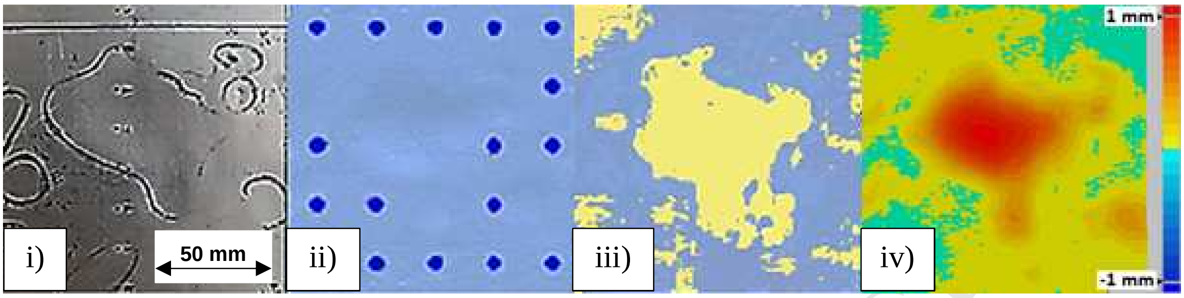

Figure 4: 3D scanning methodology; i) damaged aircraft panel surface; ii) point cloud data for the damaged surface (light blue) with grid of selected undamaged regions (dark blue); iii) 3D CAD surface (yellow) fit based on grid of undamaged regions; iv) deviation analysis color map showing dent depth (mm)

2.1. Point Cloud Generation

Point cloud data for the damaged aircraft panels was gathered using a FARO® Edge 3D scanning apparatus (Figure 5) comprised of a FARO® Laser Line Probe and SmartArm technology with single point repeatability from 0.024-0.064 mm, which indicates that the position of a point measured multiple times using the probe is expected to vary by less than 0.064 mm. The point cloud data for one of the two flat aircraft panels is illustrated in Figure 6. The data acquisition process was performed using Geomagic Design X software.

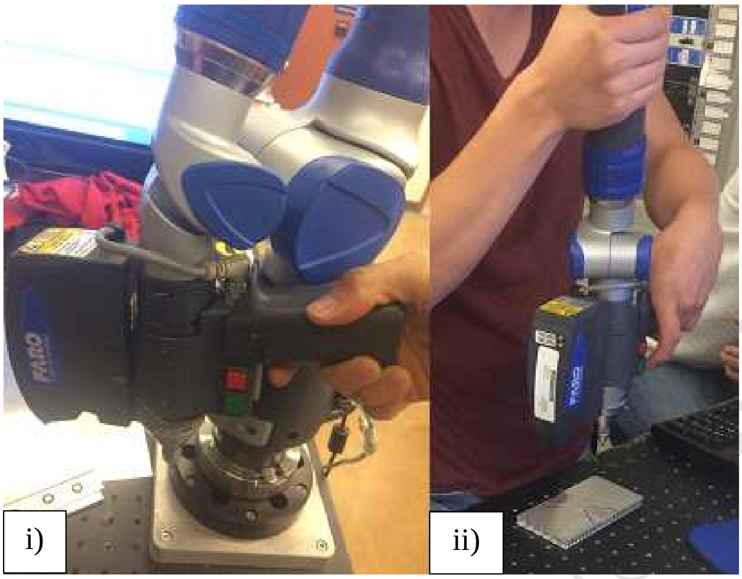

Figure 5: FARO® Edge 3D scanning apparatus. i) scanning pistol and base of scanning apparatus, ii) scanning pistol orientation during scan of aluminum honeycomb coupon

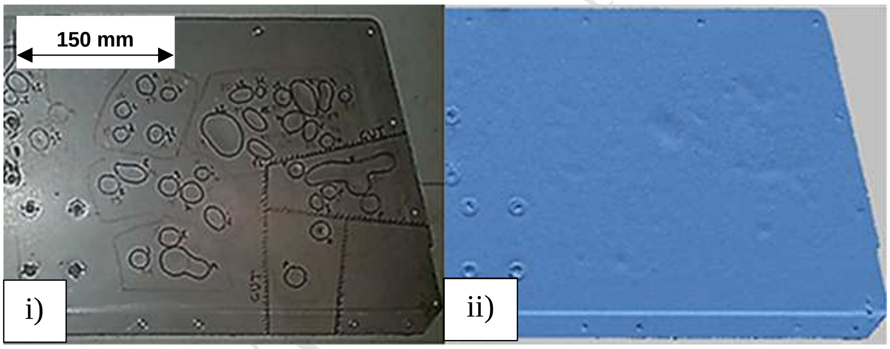

Figure 6: Flat, dented aircraft panel. i) photograph, ii) corresponding 3D point cloud rendering

2.2. Dent Length and Area Measurement

Dent area and length were determined using color map data and the Open Source software ImageJ as they could not be determined directly using the point cloud data tools available in Design X. Dent length and area do not contain indentation depth information, and thus these size measurements are not proportional to the damage based on dent depth; however, these parameters are important based on the damage limits defined by the OEM. The area measurement represents planar area, making it independent of dent depth. The procedure for measuring dent length and area is described below, and is illustrated in Figure 7.

1. A second deviation analysis is performed on the existing point cloud data within Design X with the *color bar* setting set to *solid color*. This procedure yields a color map that clearly outlines the perimeter of each dent, as shown in Figure 7 ii), where any deviation beyond the defined tolerance is presented as a single color (dark blue).
2. The color map is converted to an 8-bit greyscale image using ImageJ, as shown in Figure 7 iii). Although not used in this study, the image may also be processed using sharpening or despeckling, which reduces noise and may enhance the analysis of more complex damage regions. For the analysis of curved geometries, the Design X *Normal To* function is used on the 3D CAD surface to rotate the color map such that it is perpendicular to the viewer and normal to the panel surface.
3. A unit scale in pixel/mm is defined using known image dimensional information provided in Design X.
4. The parameters of interest such as area and maximum dent length are output from ImageJ.

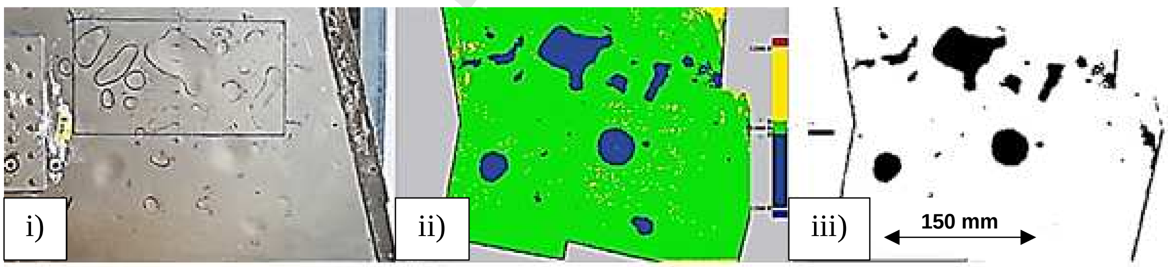

Figure 7: Dent length and area assessment; i) damaged panel; ii) color map identifying dents; iii) measurement of selected shapes in greyscale image

2.3. Recreation of Original Panel Surface

For each panel, a 3D CAD surface was fit to a grid of circular point cloud regions corresponding to the original, undamaged surface of the panel. Each region was prescribed a diameter of 5 mm with grid spacing defined by the results of a convergence study to recreate the undamaged panel surface. The circular regions of point cloud data were defined using the *Region-Insert* function in Design X, with all the defined regions being collectively referred to as a *Region Group*. Regions were selected such that they were adjacent to, but did not include, the damaged regions. A 3D CAD surface was then fit to the *Region Group* using the *Mesh Fit* tool, which resulted in an approximation of the original, undamaged surface of the panel. Convergence studies were performed for both flat and curved panels to assess the effects of varying the undamaged region spacing on measured dent depths, lengths and areas, and thus the accuracy of the recreated panel surface. In each study, the spacing of the regions was decreased until convergence was achieved, as defined by a change in average percent difference of less than 5% between successive measurement samples, given by:

$$Average\ \%\ Difference = \frac{\sum_1^n \frac{abs(x_i - x_{i-1})}{x_{i-1}}}{n} \times 100\% \qquad \text{Eq. 1}$$

where *i* is the current spacing, and *n* is the number of dents identified on the inspection surface. Regions lying within identifiable dent impressions were manually omitted because dented surfaces do not represent part of the original surface geometry of the panel.

2.3.1. Convergence Study – Flat Panel

A convergence study was performed on a 225 × 225 mm^2 area of one of the flat aircraft panels with 18 dent impressions to determine the effects of varying the spacing between undamaged regions on the dent depth, length and area measurements. It is possible to perform the method on entire aircraft panels as opposed to smaller surface areas; however, it is more efficient to scan and analyze localized damage regions due to the processing times of the software.

This study resulted in six *Region Groups* with different region spacings as listed in Table 3. Figure 8 shows the color map results for *Region Groups* 1, 2, 4 and 6, where green represents the undamaged surface based on a minimum dent depth value, and the other colors indicate dent depth. The final dent impressions are numbered in the color map results for *Region Group* 6. Many of the dent impressions were not identifiable in *Region Group* 1; however, as the spacing was decreased, consistent dent impressions developed. Figure 9 shows the convergence curve of the average percent different between successive decreases in spacing (Eq. 1) for the flat panel study for dent depth, length and area, respectively.

Table 3: Region Spacing for Flat Panel *Region Groups*

Region Group	*Number of Regions	Spacing [mm]
1	4	220
2	16	73.33
3	36	44
4	64	31.4
5	100	24.4
6	121	22

*Number of regions indicates maximum number, whereas the number may be smaller if the regions fall in a location where there is a dent

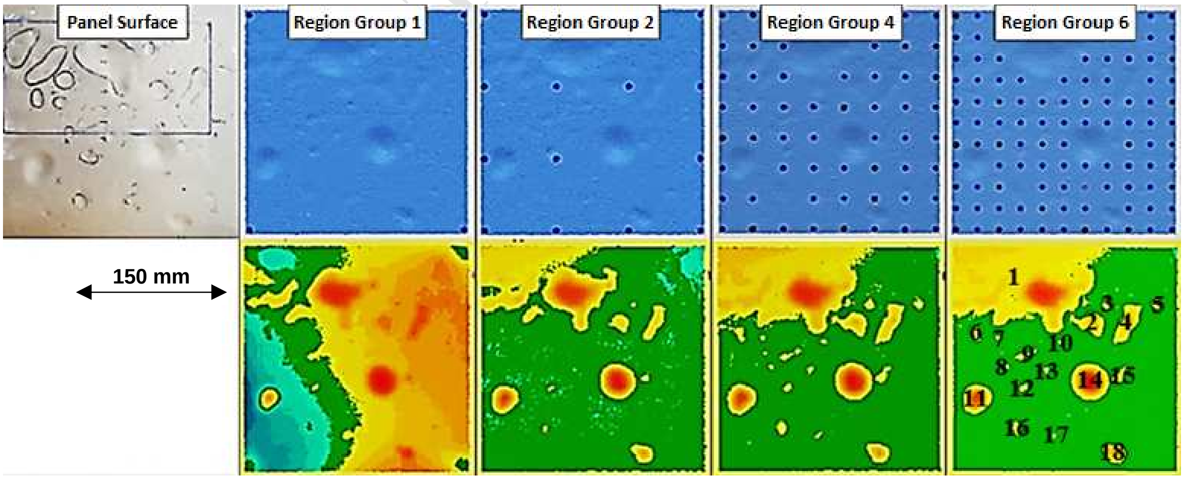

Figure 8: Illustration of flat panel convergence study; *Region Groups* comprise a grid of circular undamaged regions with spacings defined in Table 3

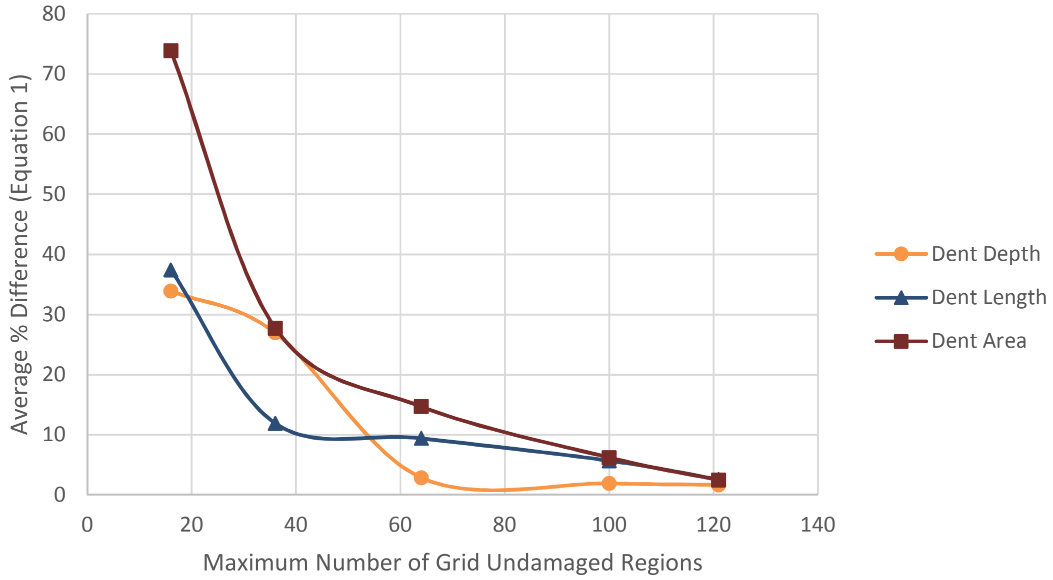

Figure 9: Average % difference evaluated using Equation 1 for *Region Groups* 2 to 6 demonstrating convergence of dent depth, length and area measurements on flat panel. Note: Measurements included in Equation 1 were only those from identifiable dent shapes for the current *Region Group*

The results of the flat panel convergence study showed that the accuracy of the measurements was improved when the spacing of the selected undamaged regions was decreased. This indicates that a convergence study based on decreasing the spacing between undamaged regions can be used to assess the accuracy of the recreated, undamaged panel surface and the resulting measurements of dent depth, length and area. Quantification of the dent area required the smallest spacing of 22 mm (*Region Group* 6) between undamaged regions, whereas dent length only required a spacing of 24.4 mm (*Region Group* 5) and dent depth a spacing of 31.4 mm (*Region Group* 4) to achieve convergence according to Equation 1. This indicates that dent area is the measurement that is the most sensitive to the accuracy of the undamaged surface fit, and that the undamaged region spacing required for convergence may differ based on the measurements required for the inspection. It is hypothesised that the degree of sensitivity observed for each measurement is a result of the degrees of freedom attributed to said measurement. Dent depth is a single length measured between the static point cloud and the changing recreated panel surface, and may be considered as having one degree of freedom. Dent length is a length measured between two points whose locations depend on the changing recreated panel surface, and may be considered as having two degrees of freedom. Dent area may be approximated as having the number of degrees of freedom for length squared, or four degrees of freedom.

2.3.2. Convergence Study – Curved Panel

A convergence study was also performed on a 125 × 125 mm^2 area of the curved aircraft panel with eight dent impressions to determine the required undamaged region spacing for the dent depth, length and area measurements.

This study resulted in nine *Region Groups* with different region spacings as listed in Table 4. Figure 10 shows the color map results for *Region Groups* 1, 2, 4 and 6, where green represents the undamaged surface based on a minimum dent depth value, and the other colors indicate dent depth. The eight dent impressions are numbered in the color map results for *Region Group* 9. Many of the dent impressions were not identifiable in *Region Groups* 1-3; however, as the spacing was decreased, consistent dent impressions developed. Figure 11 shows the convergence results for the curved panel study for dent depth, length and area, respectively, based on Equation 1.

Table 4: Region Spacing for Curved Panel *Region Groups*

Region Group	*Number of Regions	Spacing [mm]
1	4	220
2	16	73.33
....		
7	144	10.91
8	169	10
9	196	9.23

*Number of regions indicates maximum number, whereas the number may be smaller if the regions fall in a location where there is a dent

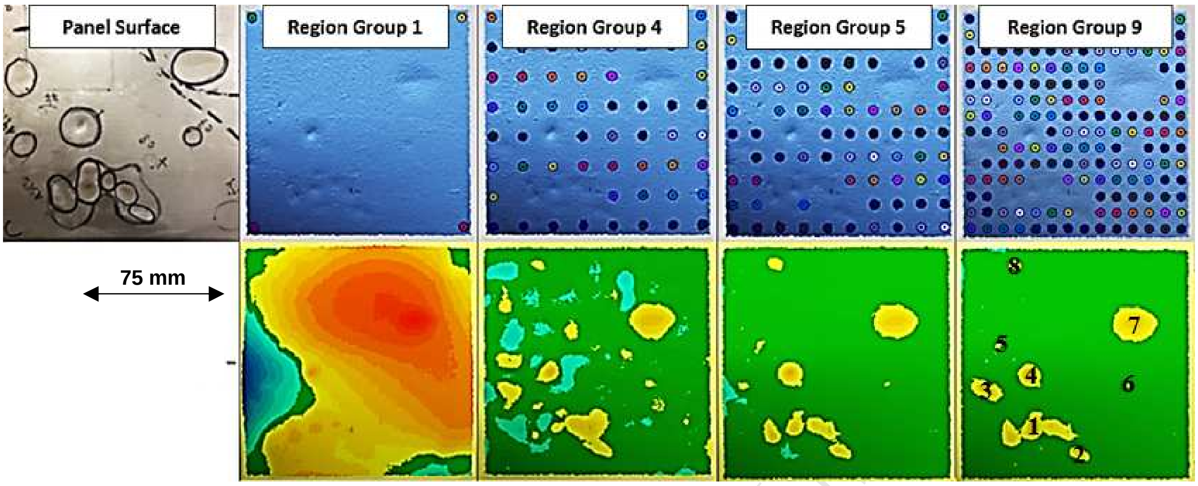

Figure 10: Illustration of curved panel convergence study; *Region Groups* comprise a grid of circular undamaged regions with spacings defined in Table 4

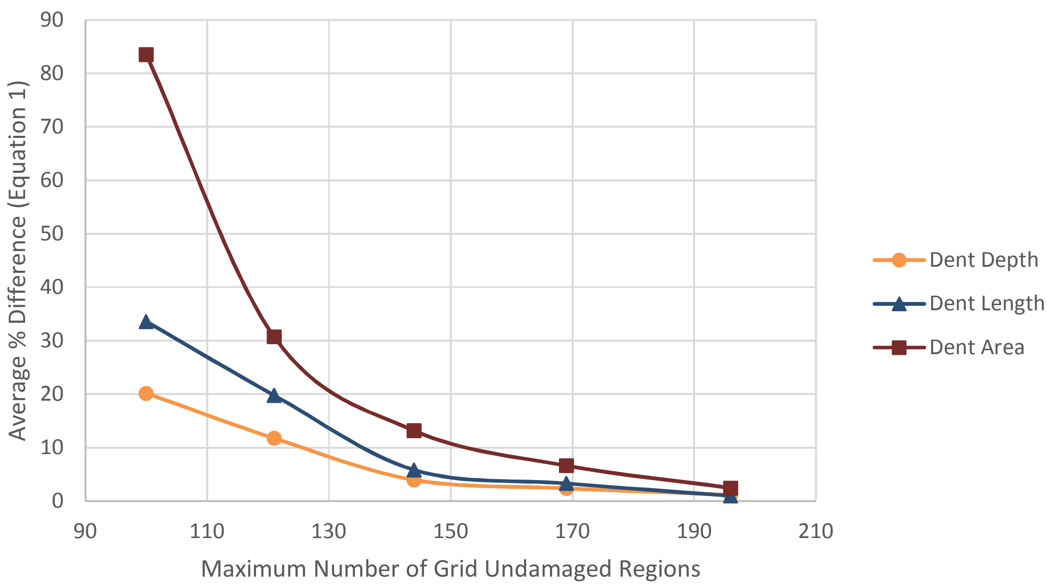

Figure 11: Average % difference evaluated using Equation 1 for *Region Groups* 5 to 9 demonstrating convergence of dent depth, length and area measurements on curved panel. Note: Measurements included in Equation 1 were only those from identifiable dent shapes for current *Region Group*

Figure 11 showed that dent area required the smallest region spacing of 9.23 mm (*Region Group* 9), whereas dent length only required a spacing of 10 mm (*Region Group* 8) and dent depth a spacing of 10.91 mm (*Region Group* 7) to achieve convergence according to Equation 1. When comparing the flat and curved panels, it was seen that a smaller undamaged region spacing was required to achieve convergence in the curved panel study for all three measurements. For dent area, convergence occurred at a spacing of 9.23 mm for the curved panel as compared to 22 mm for the flat panel. This indicates that recreation of the undamaged surface for curved panels requires a finer resolution of undamaged regions than for flat panels in order to properly capture the surface curvature. It is also noted, however, that damage characteristics such as pattern, shape and size are also different between the two panels and contribute to the undamaged region spacing required for convergence. For both flat and curved panels, dent depth was seen to be the least sensitive measurement to the undamaged region spacing, while dent area was the most sensitive.

2.4. Dent Depth Measurement

Once the 3D CAD surface approximating the undamaged panel was created, the deviation between the point cloud data and surface fit was quantified using the *Deviation Analysis* tool in Design X [36]. The *Deviation Analysis* tool measures the distance between the fitted surface and the point cloud data normal to the surface fit. The values obtained using the *Deviation Analysis* tool correspond to dent depth as illustrated in Figure 12.

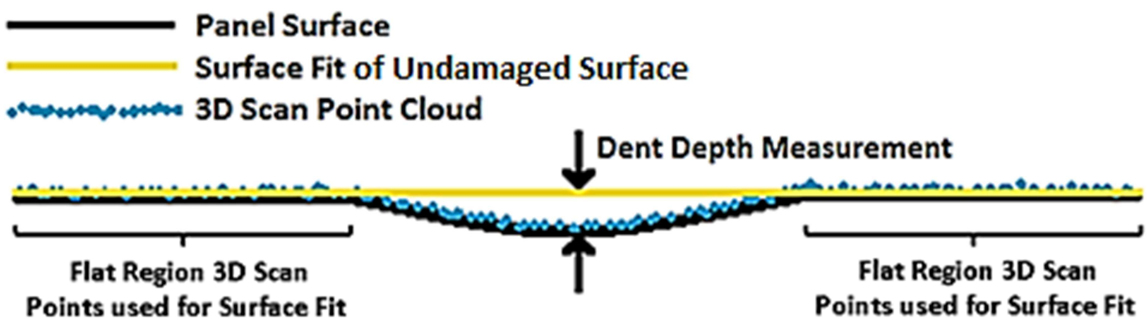

Figure 12: Illustration of the dent depth measurement. Scan data represents the point cloud rendering of the physical damaged panel surface, and the surface fit is an approximation of the original, undamaged panel surface

The deviation analysis produces a color map quantifying the difference between the point cloud representation of the damaged panel and the 3D CAD surface approximating the undamaged panel. Figure 13 shows the color map results for one of the flat aircraft panels transposed onto an image of the actual panel.

Figure 13: Deviation analysis color map (mm) with the results transposed onto an image of the physical panel

It is generally accepted in aircraft structural inspection that Barely Visible Impact Damage (BVID) is a limit that is defined as damage that can be detected visually, under standard lighting conditions, at a distance of approximately 5 feet. Depending on the size and shape of the damage, this generally corresponds to a dent depth between 0.25-0.50 mm, and any damage below the BVID threshold generally falls within the negligible damage limit. In the current study, dents were identified as having a dent depth greater than 0.1 mm. This value is referred to as the minimum dent depth, and was established with the intent of matching the color map results of the dents to those visually identifiable by inspection personnel. This ensured that the proposed method could support identification of BVID dents in accordance with the requirements of the panel manufacturer. The value of 0.1 mm used in this study was established based on the study described in Section 2.3.1; however, it may be changed based on the specific application of this NDE method.

2.4.1. Minimum Dent Depth Study

A series of three dents with different depths were created on an aluminum-faced honeycomb sandwich coupon using a 1 kg steel ball of 50.8 mm (2 in) diameter dropped at different heights. Dent depths of 0.04 mm, 0.10 mm, and 0.29 mm were measured using the 3D scanning method, with only the 0.29 mm dent qualifying as BVID. The coupon was subsequently cut through the centers of the dents using an automated diamond blade saw, and underlying core damage was identified using a microscope. The core damage is shown in Figure 14.

Figure 14: Core damage in experimental coupon for face sheet dent depths of 0.04 mm (left), 0.10 mm (middle), and 0.29 mm (right)

The 0.04 and 0.10 mm dents in Figure 14 were below the BVID cut-off, and the resulting core and face sheet damage would not be expected to affect residual panel strength. The 0.29 mm dent, however, resulted in more extensive damage including buckling and crushing of the cell walls. A conservative value of 0.1 mm was selected for the minimum dent depth, which is well below the commonly accepted BVID limit. On the color maps, for example in Figure 13, areas that are green represent locations where the deformation of the panel is less than 0.1 mm from the recreated panel surface.

3. Results

Measurements for dent depth, length and area were obtained for the three damaged aircraft panels using the 3D scanning methodology outlined in Chapter 2, and were compared to measurements taken using the Starrett 643J dial depth gauge, a tool currently used for in-service inspection of damaged aircraft panels. Undamaged region spacings of 22 and 9.23 mm were used for the flat panel and curved panel analyses, respectively, based on the results of Section 2.2.1 and 2.2.2. 54 dent impressions were measured on the two flat panels, and 74 dents on the curved panel.

3.1. Dent Depth

The 3D scanning inspection method was validated by comparing dent depth data to measurements taken using the depth gauge. The results of these comparisons are shown in Figures 12 and 13 for the flat and curved panels, respectively.

Figure 15 shows that for the 54 flat panel dents, a maximum absolute difference of 0.09 mm and deviation of 0.04 ± 0.06 mm for a 95% confidence interval were obtained between the 3D scanning and depth gauge measurements. Figure 16 shows that for the 74 curved panel dents, a maximum absolute difference of 0.095 mm and deviation of 0.04 ± 0.05 mm for a 95% confidence interval were obtained. The solid lines with slopes of 1 indicate identical measurements between both methods, and the flat and curved panel results yielded linear fit R^2 values of 0.9743 and 0.9209, respectively.

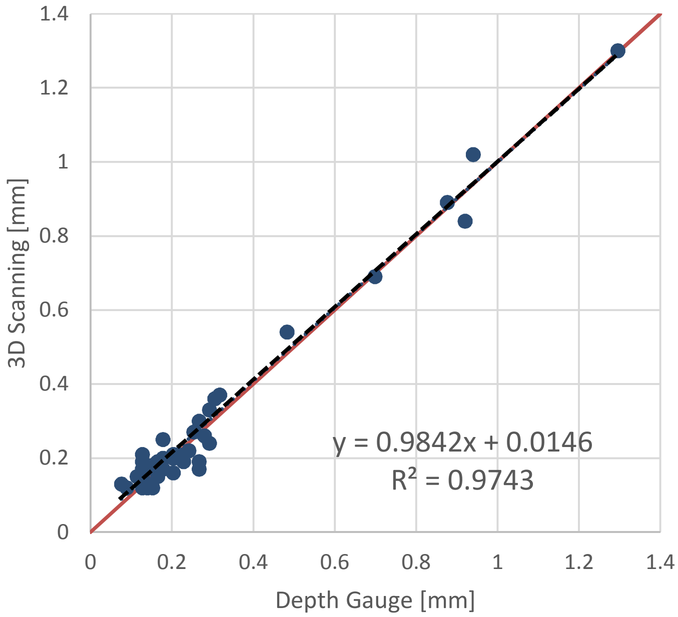

Figure 15: Dent depth (3D scanning) plotted against dent depth (depth gauge) for flat panels. The red line represents identical measurements and the dotted line is the linear data fit.

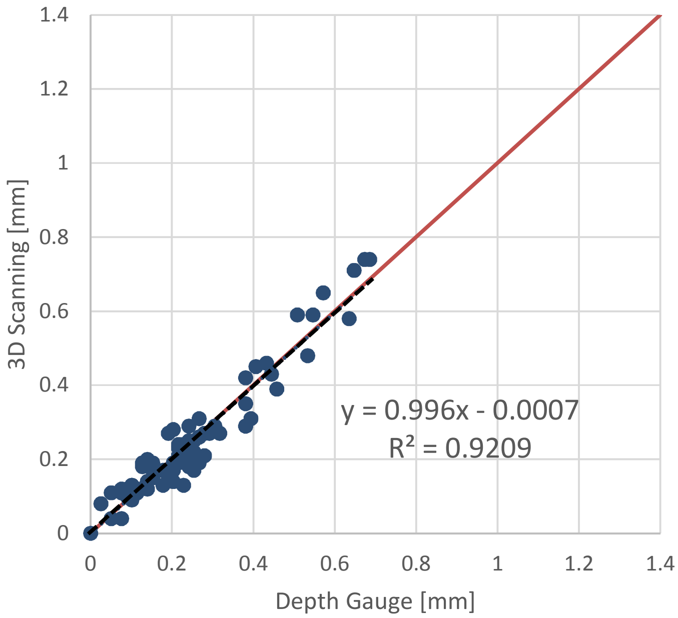

Figure 16: Dent depth (3D scanning) plotted against dent depth (depth gauge) for curved panel. The red line represents identical measurements and the dotted line is the linear data fit.

3.2. Dent Length and Area

Figure 17 illustrates five individual dent regions identified using the 3D scanning method and ImageJ postprocessing, and compares them to the dent areas calculated using the manual technique performed in the field. The method commonly described in the SRM conservatively approximates each dent as being circular with a diameter equal to the largest dent length measured using a ruler. Table 5 lists the areas of each dent as calculated using both the proposed 3D scanning method and the method outlined in the SRM. Dent length and area describe the in-plane size information of a damage region. However, the collective dent depth, length and area information obtained by the proposed method describe the 3D geometry of a damage region, where dent depth describes the extent of damage normal to the panel surface, and dent length and area describe the extent of damage within the plane of the panel surface. Here, damage is defined based on the SRM in terms of dent depth, length and area.

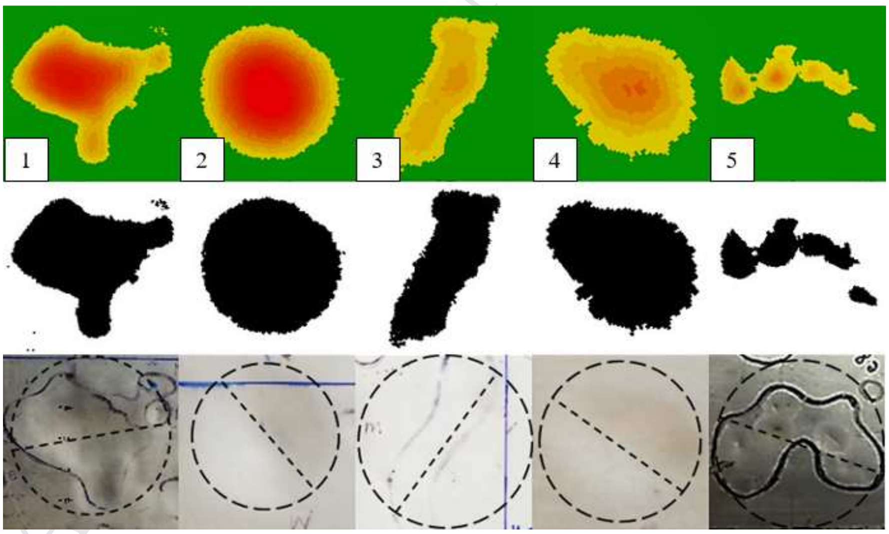

Figure 17: Dent shape comparison; i) 3D scanning method; ii) ImageJ image processing; iii) manual method of area approximation using dent length as the diameter of a circle. Scale information shown in Table 5.

Table 5: Dent area measurement comparison

Dent	3D scanning method (image processing) [mm^2]	Manual SRM method (circular area) [mm^2]	% Difference
1	18.75	35.26	88
2	10.12	11.34	12
3	7.01	21.24	203
4	4.53	7.07	56
5	3.70	20.42	452

4. Discussion

It was shown in Section 3.1 that the 3D scanning method can measure dent depth to the same level of accuracy as the manual depth gauge currently used in-field. The benefits of using 3D scanning in terms of measuring dent depth, length and area are discussed in this section.

4.1. Dent Depth

Comparisons between the depth gauge and 3D scanning measurements provided in Section 3 indicate that the results obtained using the 3D scanning method agree well with those obtained using manual inspection methods, while providing significantly higher data density in a shorter period of time. The dent depth accuracies for the flat and curved panel measurement samples were seen to be similar, both yielding maximum absolute differences of approximately 0.09 mm and deviation values of 0.04 mm. On the contrary, the flat panel sample yielded a higher linear fit R^2 value of 0.9743 compared to the R^2 value of 0.9209 for the curved panel sample, indicating that higher consistency may be easier to achieve for panels with simple surface geometries.

Application of the 3D scanning method for each aircraft panel took approximately 15 minutes to complete, whereas inspecting the same panels using the depth gauge took 45-60 minutes. In addition, because each deviation measurement is made normal to the 3D CAD surface in the Design X software, the analysis performed is independent of the reference frame or coordinate system, and panels may thus be oriented in any arbitrary direction when performing the laser scanning. The process of probing for maximum dent depth values may be facilitated by importing the point cloud data and 3D CAD surface developed in Design X into Geomagic Control X software, which supports automated identification of the largest deviation values between a point cloud and CAD model for a specified tolerance. There is also potential for the entire method procedure as outlined in Section 2 to be automated using Geomagic Wrap software or by developing an original automated program.

The 3D scanning method demonstrates a smaller range of measurement variability compared to conventional depth gauge measurements. This was evaluated for the dents on the curved panel surface shown in Figure 2. It was found that manually rotating the position of the depth gauge about the center of the four dent impressions and taking depth measurements at five different angles with respect to the longitudinal axis of the panel yielded variability up to 0.102 mm. The depth values obtained for these dents after five repetitions of the 3D scanning method only varied by a maximum of 0.028 mm. This indicates that the variation in dent depth measurements between different inspection personnel using manual methods is likely to be larger than when using the 3D scanning method.

4.2. Dent Length and Area

For the five dents evaluated in Figure 17, the 3D scanning method always measured a dent area less than that calculated using the circular area approximation method. The results also showed that for approximately circular dents, the manual method and the 3D scanning methods provide the most similar results as demonstrated for Dent 2. The circular area method was seen to be grossly conservative for more complex dent shapes with larger aspect ratios such as Dents 3 and 5. Furthermore, Dent 5 was identified by inspection personnel as being one large impression, whereas the 3D scanning results revealed the existence of several smaller dents and resulted in a more realistic area measurement.

It was shown in the converged color map results of *Region Group* 6 in Figure 8 that Dent 1 is one large dent impression, even though inspection personnel had identified several individual dents. This was confirmed using an eddy current (EC) surface profiling technique developed by the authors in Reference [37], which yielded damage map results comparable with those of the proposed 3D scanning method as shown in Figure 18.

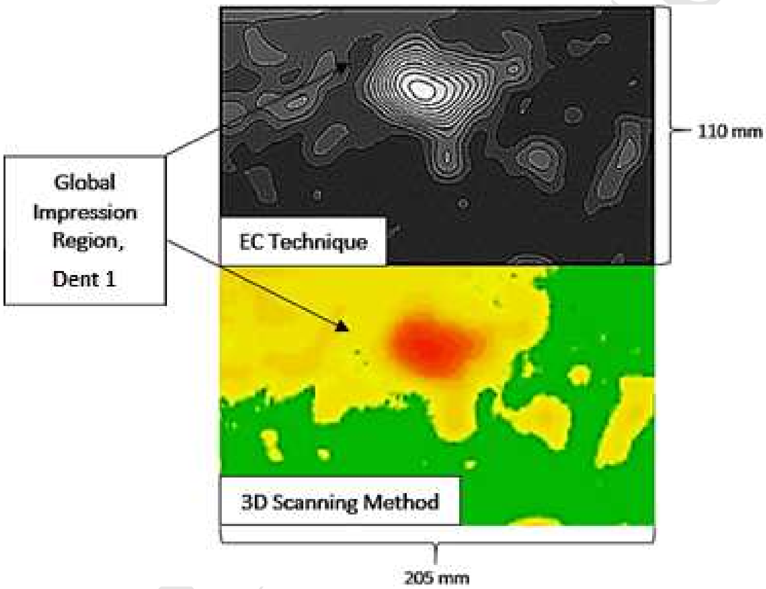

Figure 18: Dent 1 identified as global impression region using 3D scanning method (*Region Group* 6), and confirmed with eddy current results [37]

5. Conclusion

In this study, a 3D scanning-based methodology for the inspection of aircraft structural panels was developed and validated. The technique can quickly and reliably measure surface damage dimensions including dent depth, length and area. The method can identify individual dent impressions within a cluster of dents, provide accurate contouring of dent impressions, and is less susceptible to operator inconsistencies compared to conventional damage measurement techniques. Dent depth values were seen to be within 0.04 ± 0.06 mm (95%) and 0.04 ± 0.05 mm (95%) for flat and curved panels, respectively, while only requiring 25-33% of the inspection time. The 3D scanning method was thus found to provide more consistent and accurate measurement data compared to measurements obtained manually using a depth gauge and a ruler. This was particularly true for dent area, where the circular area assumption applied using the manual technique was over-estimated by up to 452% when compared to the 3D scanning method. This improvement in calculating dent area would not change the method of repair described by the OEM because aluminum honeycomb sandwich aircraft panels typically retain a dented geometry until the total denting exceeds the damage limits defined in the SRM, after which they are replaced. However, the proposed method holds the potential to extend panel lifetimes based on total dent area due to areas not being measured over-conservatively as much as over 450% as shown in Table 5. The method was not seen to overestimate the extent of damage, instead producing measurements similar to those obtained manually using a dial depth gauge.

A method for evaluating the accuracy of the surface fit approximating the original panel geometry was also proposed, which showed that the 3D scanning method can be used as a stand-alone technique without the need of a validating measurement tool or the original CAD geometry. This technique may support the extraction of surface dent measurements without removing the panel from the aircraft and would thereby reduce aircraft time on the ground. The method demonstrates potential for in-field implementation using portable 3D scanning systems as well as for automation. Implementation on larger structures such as entire aircraft fuselages may require a larger, more robust scanning apparatus; however, for the purposes outlined in this study, a portable optical 3D scanning system connected to a laptop computer would suffice for in-field inspection of structural panels in environments free of large airborne particulates or debris. The requirements for automation would include software automation such that undamaged regions of the 3D point cloud data were automatically identified and selected before fitting of the 3D CAD surface, and dents that are outside the allowable damage limits of the given panel could be automatically identified by applying the damage limits to the deviation analysis. Compared to the circular approximation of area which has been traditionally used due to its ease of execution, other damage parameters such as dent volume could be determined using the proposed method, which may be more meaningful in terms of identifying allowable damage limits. The digital nature of the measurements also provides a convenient means of recording the size and location of dents for monitoring damage growth.

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Surface Damage Evaluation of Honeycomb Sandwich Aircraft Panels Using 3D Scanning Technology

Highlights:

- An NDE method using 3D scanning is proposed to measure surface dent dimensions on aircraft panels
- This method could reduce inspection times by up to 75% as compared to current in-field techniques
- Measurements of dent depth and area are more accurate and reliable than current in-field techniques
- The proposed method is used to measure dent length and area for flat and curved aircraft panels
- Novel use of convergence studies to evaluate the accuracy of the surface fit of undamaged panels