A METHOD TO IMPACT AND CHARACTERIZE DAMAGE FOR NON-STANDARD COMPOSITE SANDWICH PANELS

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ABSTRACT

Low-velocity impact causing barely-visible impact damage (BVID) on composite sandwich panels is a concern in the aerospace community. Impact may cause a reduction in stiffness and strength of a structure, and damage growth could lead to problematic aeroelastic effects or structural failure. In this study, pre-cut panels from a high-performance aircraft horizontal stabilizer were subjected to impact testing. This paper proposes a methodology for drop-weight impact testing for non-standardized sandwich panels using a fixture designed to accommodate panels of varying thickness. The fixture was used to qualitatively compare the effects of impact events on a repaired and unrepaired panel. C-scan tap test, ultrasound, radiography and laser topography non-destructive inspection (NDI) techniques were compared for both the repaired and unrepaired panels.

1 INTRODUCTION

Strong, stiff and lightweight structures are desirable in the aerospace industry, and this requirement has led to greater usage of structural composites such as sandwich panels [1]. Sandwich panels consist of facesheets bonded to a core material, resulting in a configuration that is lightweight and stiff in bending. Facesheets will carry the normal load and the core material primarily carries the shear, like the flange-web configuration of an I-beam. Facesheets are often optimized for normal tensile and compressive stresses utilizing fibre-reinforced laminates; these facesheets are adhesively bonded to a core, often a honeycomb fabricated from Nomex® or aluminum alloy. Sandwich panels are well suited for structural applications such as aircraft flooring, interiors, and aerodynamic surfaces [2].

Out-of-plane impact is a concern for sandwich panels since it can damage the facesheet, bondline and core. Mass dominated (i.e. low-velocity) impacts may cause Barely-Visible Impact Damage (BVID) such as shallow dents that are difficult to visually detect on the surface of the panel. Certain panel combinations, such as those with thicker facesheets, may be prone to significant rebounding of the facesheet, obscuring the underlying bondline and core damage [3]. Sandwich panels must be strong enough to withstand the required loading and impact damage may reduce panel static strength below acceptable levels [4]. Failure modes that are possible for a composite facesheet and an aluminum alloy honeycomb core include delamination, matrix cracking, fibre failure, disbond, core fracture, and core crushing [5] There are various parameters that influence impact damage [6], such as material properties [7], layup and ply orientation [7], boundary conditions [8], impact under a preload, core density, adhesive, curvature [9], wall-partition angle [10], size and thickness of the laminate, and projectile characteristics.

Various methods have been used to predict stiffness reduction and damage for idealized panels using analytical and empirical methods [11-14]. Numerical methods have also shown agreement with experiments [15-17]. Most previous experimental studies look at impact using standardized coupons [18], an approach which has some limitations when compared to real life aircraft sandwich panels. Real life panels are ideally suited to exploratory research and may have repairs, varying facesheet thickness, ply ramps, ply drop-offs, changes in core density, core splices, underlying structure (e.g. ribs) and airfoil geometry that leads to varying core wall partition angle. Real life panels may have experienced a complete service life, which means they are structurally conservative. Disadvantages of nonstandard panels are a lack of repeatability, the inability to produce a statistical result and challenges regarding development of a fixture to impact the panels.

2 METHODOLOGY

The sandwich panels investigated were sectioned from a high-performance aircraft stabilizer, and consist of carbon fibre reinforced plastic (CFRP) facesheets (AS4 fibres /3501-6 epoxy matrix), bonded with an epoxy adhesive (FM300) to a lightweight aluminum alloy honeycomb core (5056-H39). Panels were subjected to low-energy, non-penetrating impact and the research study goals were to:

- design a fixture that would accommodate non-standard panels;
- compare impact on a repaired and unrepaired panel; and
- compare non-destructive inspection (NDI) methods for non-standard panels.

The two panels selected for this study were a repaired and unrepaired panel which were otherwise identical with 614 μm laminate thickness facesheets consisting of 0, +/-45 and 90-degree ply orientations, and 2.3 *pcf* density core. Figure 1 shows an example of an undamaged panel before impact used as a baseline.

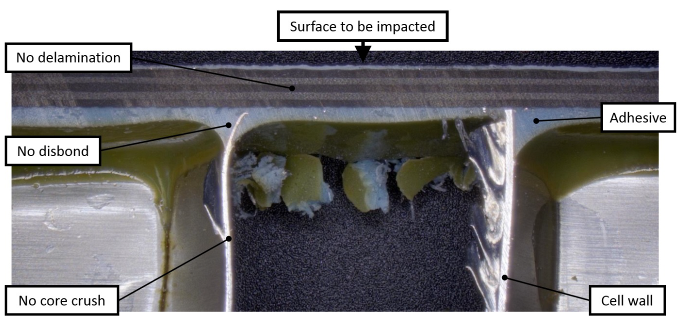


Figure 1. Section of a panel with no damage present

2.1 *Drop Tower and Fixture*

Figure 2 shows the Dynatup drop tower used, which has a double column impactor guide mechanism. The guide rails and the latch mechanism of the tower provide for a controlled drop of the impactor and crosshead assembly. All impactors used were hemispherical. The load cell, velocity detector and flag provide data for the impact energy calculation. Impact energy is determined by integrating of the load-time data [19].

Figure 3 shows the fixture designed to accommodate the non-standard panels, as a standard ASTM fixture is not capable of accommodating panels of varying shape and thickness [20]. The fixture provides for impact perpendicular to the upper facesheet using a modified Simplex 12-ton screw bell jack. An aluminum alloy platen can rotate 15 degrees from the horizontal to accommodate panels of various shape, and a 5-inch inner and 7-inch outer diameter contact ring provides a support surface similar to the support provided by ASTM D6264 [21].

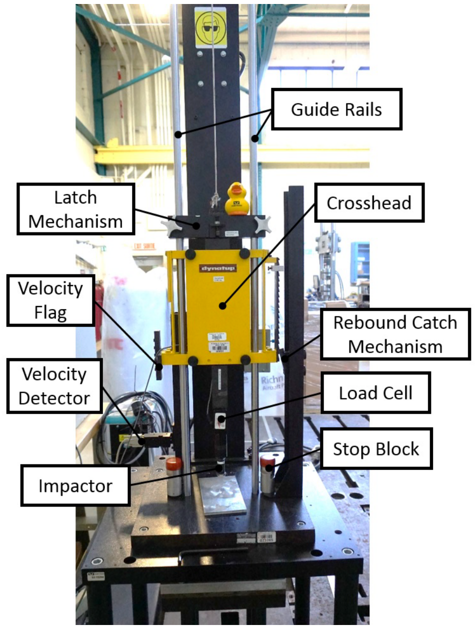


Figure 2. Drop weight impact tower components

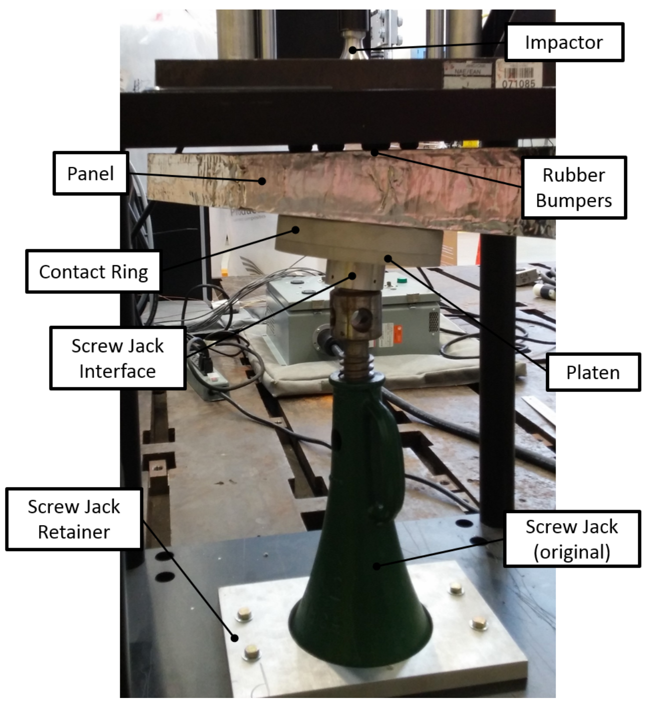


Figure 3. Fixture setup with non-standard sandwich panel.

2.2 *Characterization Methods*

Characterization of the impact damage was performed using the C-scan tap test, through-transmission ultrasound, radiography, and laser topography. Destructive characterization was performed by sectioning the panels through the damaged locations and microscopy of the cross-sections. Ultrasound was performed before impacting to confirm that there was no pre-existing damage, and laser topography was performed before and after impact to produce an exact profile of the dents.

2.2.1 C-scan tap test

A Computer-Aided Tap Tester [22] (CATT) was not available, and the test method was reproduced using an Endevco modal hammer (Model 2302-100), a EHM1209 2 *g* plastic tip, Microsoft Excel, a *1 x 1 cm* grid drawn on a transparency, a PicoScope 2204A oscilloscope and oscilloscope software. The grid was placed on the sandwich panels after impact, the grid locations were tapped using the hammer, and the contact time was plotted in Excel. As seen in Figure 5, areas that are damaged have a greater contact time, and by applying conditional formatting in Excel the damaged locations can be easily identified.

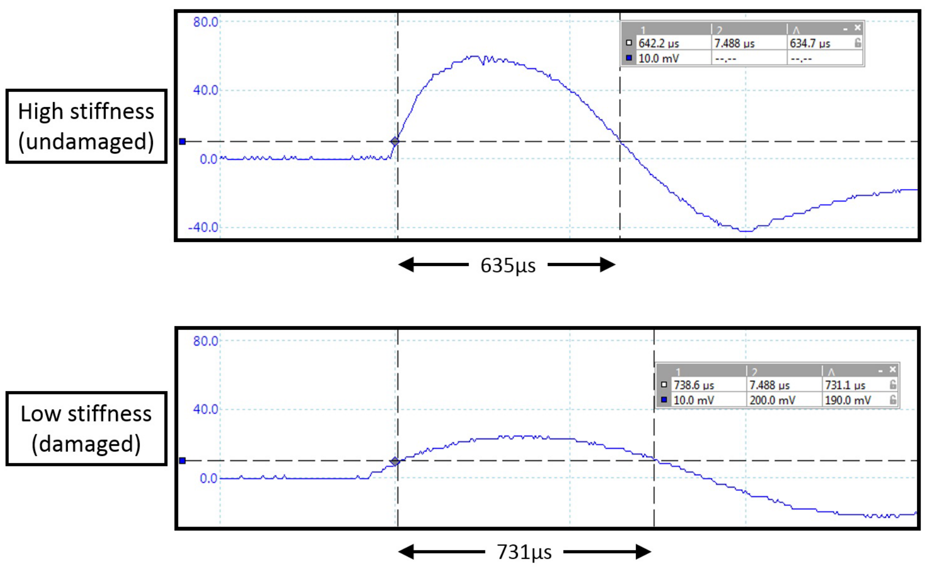
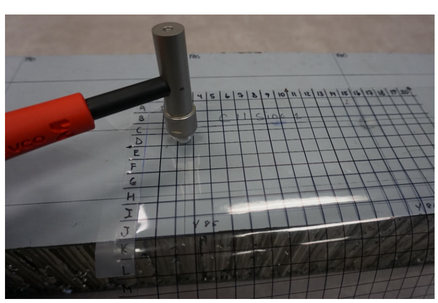


Figure 5. Voltage-time history showing high and low stiffness. Lower stiffness indicates underlying damage.



	1	2	3	4	5	6
A	449	457	457	436	436	416
B	461	502	547	502	436	416
C	494	575	702	559	440	428
D	457	547	588	502	432	428
E	432	449	428	428	428	420

Figure 6. C-scan tap test with mapped contact time.

2.2.2 Ultrasound

Through-transmission ultrasound was used to detect sub-surface discontinuities, and is capable of revealing core crush or disbond for sandwich panels [23]. The study uses a TecScan seven-axis automated ultrasonic C-scan system with a Utex pulser/receiver and Panametric immersion probes. A panel mid-scan is shown in Figure 7.

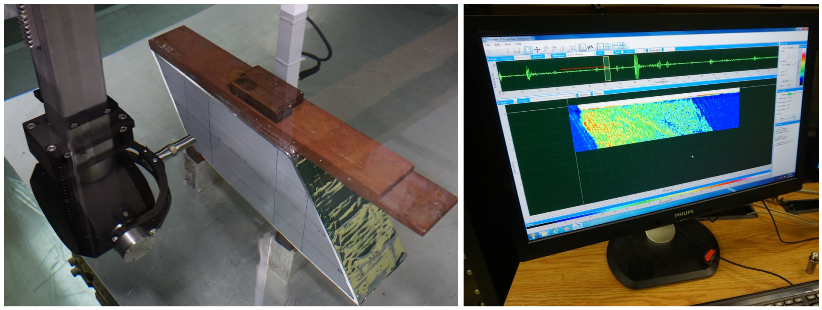


Figure 7. Panel in the immersion tank (left) and the C-scan displayed on screen (right).

2.2.3 Radiography

Radiographic inspection can reveal core crushing or laminate cracking, and was used post impact for the panels. The setup uses a Lorad LPX160 portable X-ray system for inspection using 60 kV and 4 mA for a duration of 20 seconds with 60-inch film-to-focal distance using Kodak MX125 film and Kodak processing [24].

2.2.4 Laser Topography

The most common method to size dent depth and diameter is to use a micrometer or dial depth gage and parallel bars as per ASTM D7766 / D7766M-11 [20]. However, difficulty was encountered due to the non-standard panels having ply ramps, curvature and a patch (in the case of the repaired panel). Laser topography was used by superposition of the initial topography before impact, and the post-impact topography leaving only the dent shape and profile detail. This was accomplished using the image processing toolbox within MATLAB® to translate and rotate before and after-impact topographies, and perform a subtraction of the two scans. Laser topography was performed with a CCD Laser Displacement Sensor (KEYENCE LK-086) attached to a THK actuator as seen in Figure 8. The scanning software used was TecView UT.

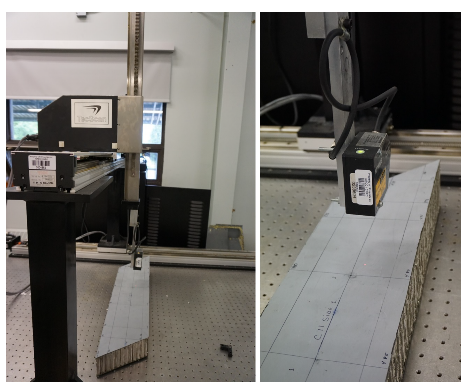


Figure 8. Laser topography set up.

2.2.5 Sectioning and Microscopy

Panels were rough cut around the damaged locations to fit within the Struers Secotom-10 precision cut-off machine. Rough pieces were sectioned using a Struers M1D20 200 *mm* diameter diamond cut-off wheel with a wheel speed of 1900 *rpm* and a feed rate of 0.100 *mm/s*. A VHX 5000 series digital microscope allowed for 3-D image stitching and was used to characterize the impact damage of the cross-sections by visually identifying the failure modes present.

3 RESULTS

3.1 Repaired and unrepaired panel study

This study focused on how damage from low-velocity impact differs between a repaired and an unrepaired panel (2). The stiffness at a repair patch is higher due to an increased effective facesheet thickness because of the additional plies, but there are additional factors that may influence the failure mode or the detectability of damage such as the presence of potting compound, foaming adhesive, additional plies, and challenges with performing a proper repair (for example, ensuring that the repair patch is well bonded to the underlying sandwich panel). The same locations were all impacted at 5 J with a 25.4 *mm* steel impactor on two otherwise identical panels. Figure 9 shows the two panels, and the impact locations identified as zone 1, 2 and 3 respectively for the unrepaired and repaired panels. One impact was on the edge of the ramp of the repair (zone 1), another in the middle of the repair (zone 2), and a third just outside the repair patch (zone 3).

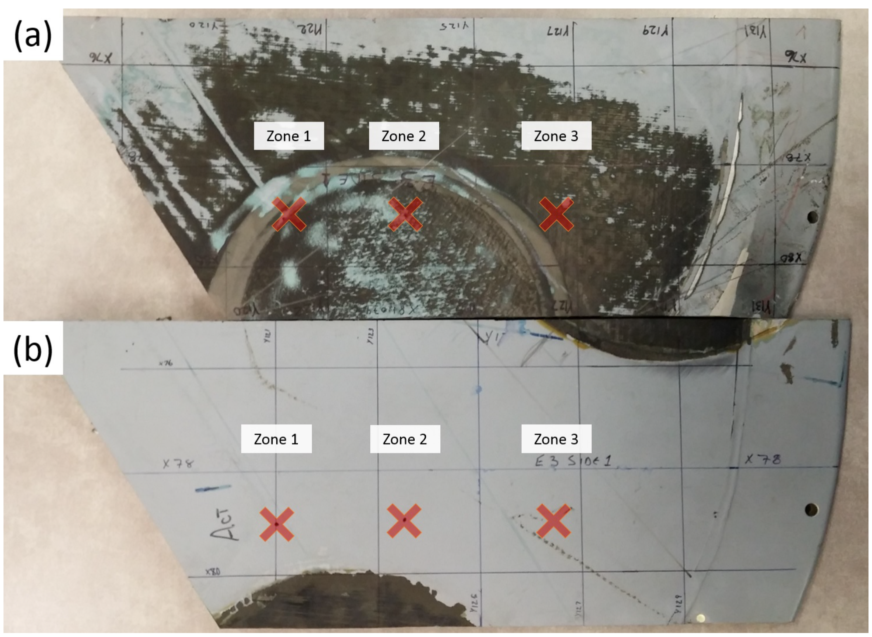


Figure 9. (a) Repaired panel with patch and (b) unrepaired panel. For the repaired panel, zone 1 is along the edge of the repair where the plies and thickness begin to taper off, zone 2 is in the center of the repair where there is increased effective facing thickness of the patch/panel combination, and zone 3 is just outside the repair patch.

Damage cross sections at zone 2 for the unrepaired and repaired panel are shown in Figure 10. Zone 2 for both panels had significant underlying damage, but the repaired panel has a much smaller external indentation than does the unrepaired panel. This is a result of the failure of the potting compound between the patch and the facesheet, allowing for the facesheet to rebound. Multiple modes of failure occurred underneath the repair patch as seen in Figure 11, including delamination, potting compound fracture and core crushing. The facesheet laminate has some delamination initiating, and the repair patch has a delamination starting underneath the second ply which has a reverse pine-tree fracture, causing delamination in the lower plies as is characteristic of thick laminates [5].

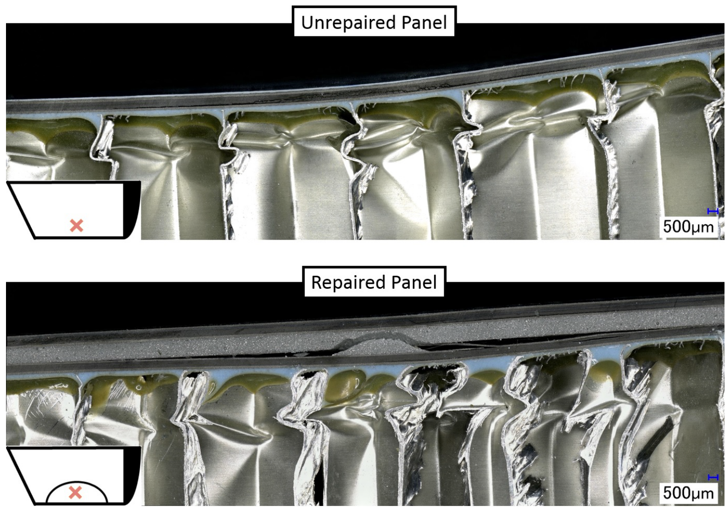


Figure 10. Unrepaired and repaired panel zone 2 cross-sections.

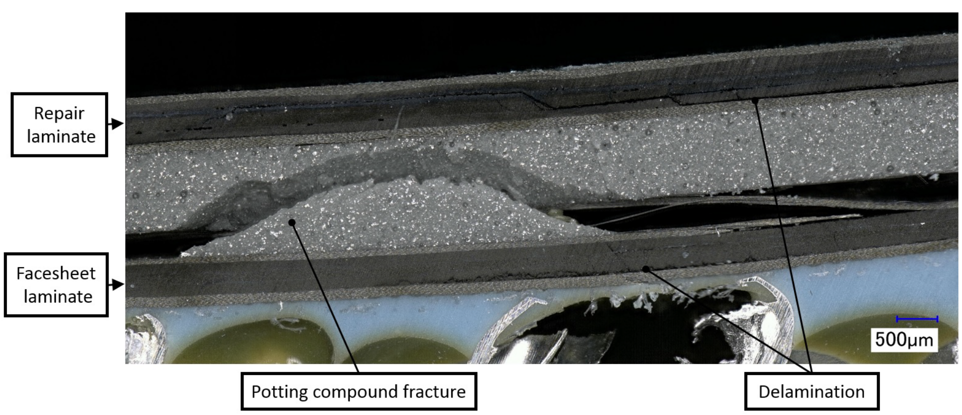


Figure 11. Repaired panel zone 2 delamination and damaged potting compound.

Zone 3 (the location just outside of the repair patch) experienced greater dent depth and laminate damage than the unrepaired panel. The repair patch appears to have acted as a boundary condition of greater fixity; being adjacent to a stiffer region does not allow much deformation so this appears to have led to greater damage.

3.2 Comparison of NDI methods

Figure 12 shows the NDI results for the unrepaired panel. Each impact was performed with a 25.4 *mm* steel impactor at 5 J. The C-scan tap test, through transmission ultrasound and laser topography easily show the damage and dent size. Note that radiography shows the core splice separating the 3.1 *pcf* core on the left from the 2.3 *pcf* core on the right (this is the same underlying structure as the repaired panel). Increased core density results in decreased damage diameter (as seen from the C-scan tap test and through-transmission ultrasound) and dent diameter (as seen from the laser topography) for a given impact energy level.

Figure 13 shows the NDI results for the repaired panel. The dashed line for the C-scan tap test outlines the patch which is detectable due to the decreased contact time. The patch is also noticeable in the ultrasound and laser topography scans, while it is barely detectable in the radiographic image as a shadow. The impact in the center of the repair patch led to a minimal dent depth (i.e. BVID) as can be seen by the laser topography deviation map in Figure 14. It should be noted that even analysis of only the post impact laser topography would reveal the impact as seen in Figure 13, even though visually the dent was not detectable and the micrometer only measured 101 μm. The laser topography does pick up the dent even though it is BVID, so this can be considered an effective NDI technique. The micrometer is not as accurate for dent profile measurements particularly for real life panels with facing thickness changes and curvature. This should be a consideration when developing inspection procedures for repair manuals, as real panels are not as easily measured as standardized coupons.

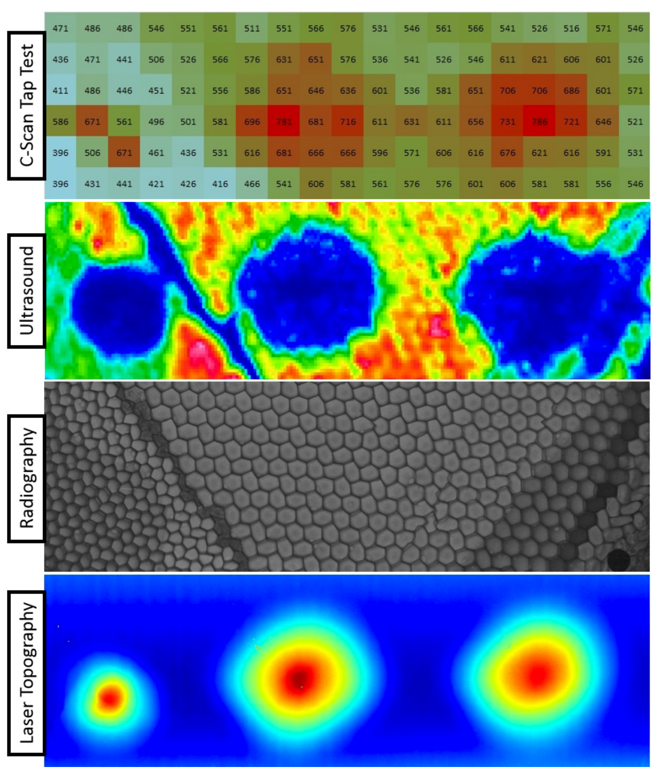


Figure 12. Unrepaired specimen NDI results. The core splice separates the 3.1 *pcf* core (left) from the 2.3 *pcf* core (right). Impact on the higher density core leads to decreased damage and dent diameter for a given energy level.

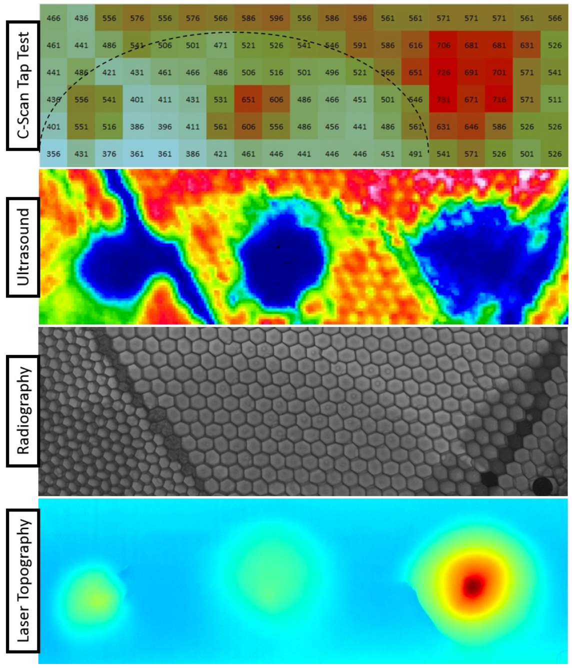


Figure 13. Repaired specimen NDI results. The dashed line indicates the patch. The zone 2 impact is BVID but detectable with the C-scan tap test, ultrasound and laser topography deviation map.

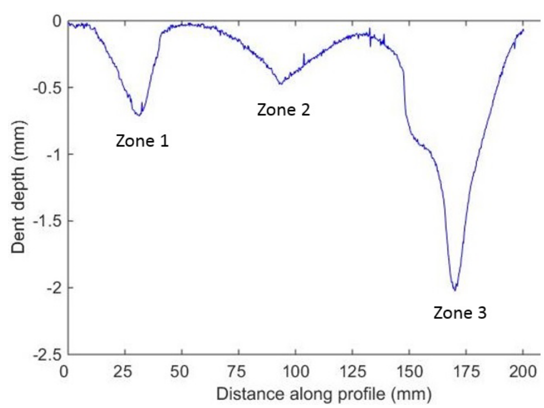


Figure 14. Post-impact laser topography dent depth profile across the repair patch and three impacts.

4 CONCLUSIONS

Non-standard panels provided unique opportunities to evaluate methods for characterizing sandwich panels. A fixture was designed to accommodate various panel shapes and sizes. Some conclusions when comparing the NDI methods were:

- Radiography was ideal for identifying internal panel features such as core splices and core density.
- The C-scan tap test was good at detecting damage and changes in core density.

- In all the cases explored, laser topography could detect all the impacts because there was surface indentation.
- None of the NDI methods could identify the failure mode with certainty including the potting compound failure.
- The NDI confirmed hidden damage that occurred underneath the repair patch which may grow in fatigue.

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