A COMPARISON OF QUASI-STATIC INDENTATION AND LOW VELOCITY IMPACT ON HYBRID COMPOSITE-METALLIC STRUCTURES USING MICRO-FOCUS COMPUTED TOMOGRPAHY

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Abstract

The equivalence of quasi-static indentation and low velocity impact loading regimes has been assessed on hybrid composite-metallic structures. The responses of the structures were assessed both in terms of the force-displacement response and the resulting damage to the different material systems. The results show that the force-displacement response follows a similar pattern between the two loading regimes. The low velocity impact tests recorded a consistently higher load but were within 10% of the quasi-static tests. Assessment of the projected composite damage area and plastic deformation of the aluminium substrate showed strong equivalence between the loading regimes based on the peak indentor displacement. This paper concludes that quasi-static indentation can be used as an analogue for low velocity impact tests in hybrid composite-metallic structures.

1. Introduction

Hybrid composite-metallic structures (HCMS) beneficially combine the characteristics of multiple materials. HCMS are used in a variety of industrial applications where particular combinations of mechanical and physical properties are sought. In service, undesired out-of-plane loading events, such as low velocity impact, can occur during manufacturing and service. There is an ongoing commercial drive to improve the design and material use of HCMS. This work aims to advance the mechanistic understanding of out-of-plane loading events on HCMS, made of an aluminum substrate, overwrapped with Carbon Fibre-Reinforced Plastic (CFRP) and Glass Fibre-Reinforced Plastic (GFRP).

The use of quasi-static indentation (QSI) as an analogue for low velocity impact (LVI) testing offers several attractive characteristics. For example, testing quasi-statically eliminates the associated oscillations from dynamic tests and allows tests to be completed with more direct control over the force and displacement applied to the test specimen. However, in order to use QSI tests to simulate LVI, equivalence must be demonstrated in terms of force-displacement response of the structure and also the resulting damage for a given load/displacement. This has been assessed in composite plates (e.g. [1]) and composite tube structures (e.g. [2]), but has not been reported in HCMS.

The presence of multiple materials, a non-symmetrical composite layup and a residual stress state makes the response of HCMS complex in comparison to traditional composite plate or tube structures when subject to impact loads [3]. In HCMS many damage mechanisms may be anticipated, such as: fibre breaks, delamination, intra-laminar cracks, metallic yield and interface debonding between the different material systems. Previous work used micro-focus X-Ray Computed Tomography (μCT) for

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detailed sub-surface damage assessment at a series of intervals throughout an interrupted QSI test to describe the progression of damage mechanisms in HCMS [4]. In this study instrumented impact tests were completed at comparable peak force and displacements to the QSI tests in order to assess the equivalence of both the load response and the nature and extent of the resulting damage. The contribution of each material system to the overall impact response and the initiation and progression of different damage mechanisms within a HCMS is assessed.

2. Method and Materials

2.1. Quasi-Static Indentation

Quasi-static indentation was conducted on a standard electromechanical test machine. A 16mm hemispherical indentor was used. Test samples were supported with a 150mm long steel block with a shallow angle v-groove for central location of the tubular geometry. Force-displacement data was recorded during the loading and unloading phase of the test at a loading rate of 2mm/min for all tests. Due to limitations of the experimental setup in compression tests the displacement measurement was taken at the crosshead of the machine. In order to account for any flexibility in the test machine a compliance test was completed. The indentor was loaded onto a rigid steel block of similar height to the sample and the displacement was recorded. This was used to calculate a compliance correction factor that was then applied to all QSI tests to account for the compliance of the load train in the measured load-displacement data.

2.2. Low Velocity Impact

All controlled impacts were conducted on an Instron™ CEAST 9350 drop tower. For each impact 10,000 data points were collected at a sampling frequency of 500kHz. An impactor of identical geometry to the QSI tests was used and the samples were supported using the same v-groove block. Two lightly secured straps were used to retain the specimen in the support block during impact to prevent the specimen bouncing out.

2.3 Computed Tomography

The CT scans were completed on a Nikon Metrology HMX µCT scanner at the µ-VIS centre, University of Southampton. A custom jig was used to offset the sample from the centre of rotation to complete a local region-of-interest scan of regions of the sidewall. The scanner has a 225kV X-ray source and Perkin-Elmer 1621 2048 x 2048 pixel flat panel detector. An electron accelerating voltage of 170kV was selected, with a tungsten reflection target and a beam current of 151µA. 3142 equiangular projections were aquired through 360º rotation of the sample, with sixteen frames per projection taken to reduce noise. 3D reconstruction was performed using a filtered-back projection algorithm implemented in CTPro 3D. The resulting volumes had an isometric voxel size of 50µm. Image processing and analysis was completed using the software packages ImageJ and VGStudio max 2.1.

2.4 Sample Details

The samples tested in this study were specially manufactured for the purposes of this work. The HCMS investigated was made of a 6061-T6 aluminium alloy shell, carbon fibre reinforced plastic (CFRP) and glass fibre reinforced plastic (GFRP). The thicknesses of the aluminium, CFRP and GFRP were 2mm, 5mm and 1mm respectively giving a structure OD of 150mm. The composite layers were filament wound in a combination of circumferential and wider angle helical warps onto the aluminium shell and cured in an out-of-autoclave process.

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2.5 Experimental Method

A total of six samples were tested in this study. Two samples were loaded in separate interrupted QSI tests. Ex-situ CT scans were completed in the unloaded condition and at each load steps to quantify the damage to the structure. Four samples were then impacted at energy levels which broadly corresponded to the inspection points from the QSI tests.

3. Results

3.1 Force-displacement comparisons

All the load data presented in the paper has been normalised based on the peak force recorded in the highest energy impact case. Figure 1 is a plot showing a comparison of the force-displacement response of the complete interrupted QSI test and the highest energy impact sample. Both loading regimes demonstrate a broadly similar force-displacement response. An initial high structural stiffness response was observed up to ~1mm displacement followed by a section of reduced structural stiffness up to ~8mm displacement where a load drop feature occurs in both loading regimes.

A plot of peak force versus peak displacement for all tests is presented in Figure 2. Both loading regimes demonstrate a strongly linear relationship with R^2 values of 0.99. The LVI load case demonstrates a consistently higher load than the QSI case for comparable displacements. The discrepancy in the peak loads between the two loading regimes is of the order of 10%, which is similar to the values observed by Bull et al. in a comparable study on CFRP plates [1].

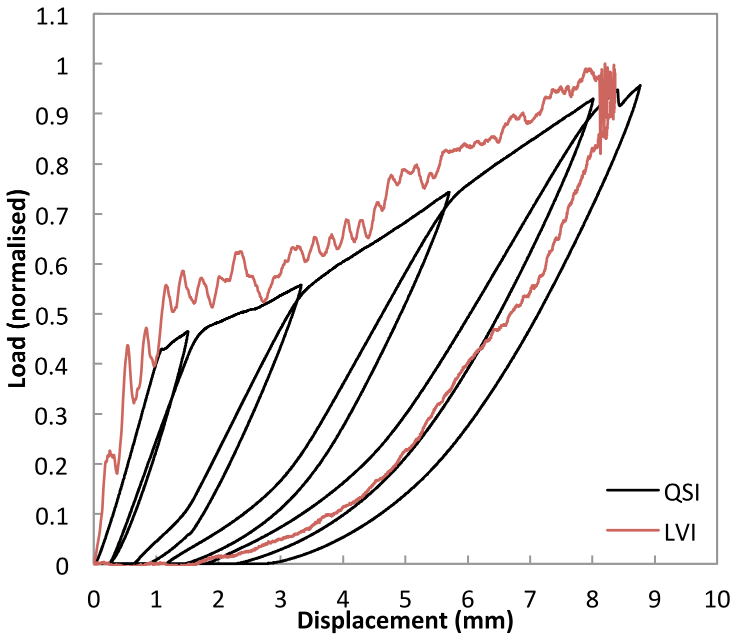

Figure 1. A comparison of the force-displacement response of HCMS subject to low velocity impact and quasi-static indentation

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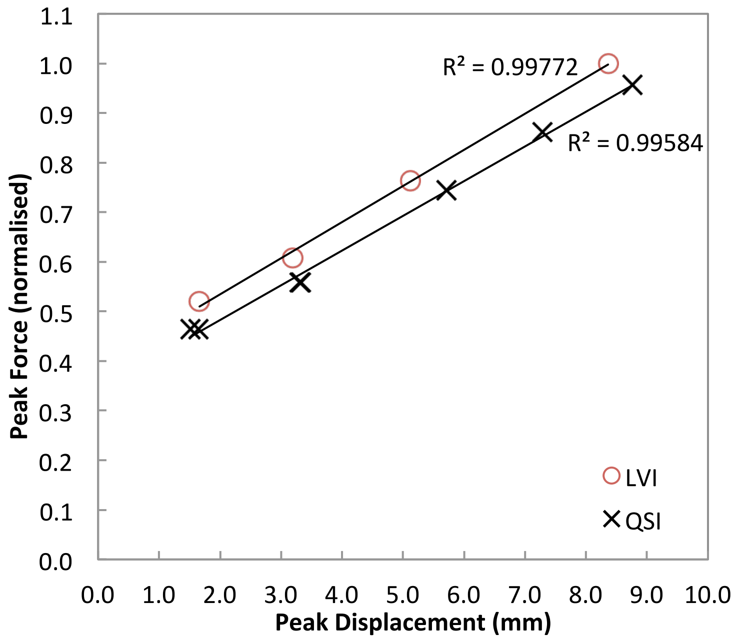

Figure 2. A comparison of the peak force versus peak displacement between low velocity impact and quasi static loading conditions.

3.2 Damage assessment

3.2.1 Qualitative damage assessment

A detailed description of the initiation and progression of the different damage mechanisms in HCMS under QSI loads has been presented previously [4]. A representative CT slice from the centre of the impact/indent location for the top load of the QSI tests and the highest energy impact case is shown in Figure 3. Qualitative assessment of the two slices indicates that broad similarities exist between the damage states of the structure under the two loading conditions. Separation between the aluminium substrate and the CFRP layer has occurred to a similar extent and at a similar location. Two differences are highlighted on Figure 3a. Marker (i) highlights that the outermost CFRP delamination, comparing this location to Figure 3b it can be see that the crack opening displacement is greater in the QSI case. Marker (ii) highlights the indent location. A larger local surface indentation can be seen in the QSI in comparison to the LVI case.

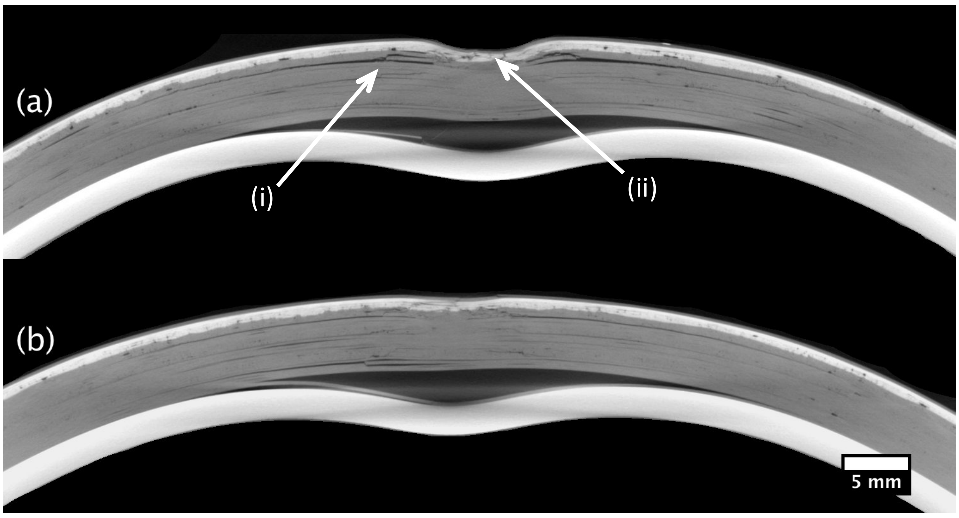

Figure 3. A central CT slice from comparable load steps under (a) quasi-static loading and (b) low velocity impact.

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3.2.2 Quantitative damage assessment

To quantify the different damage mechanisms in the HCMS two measurements were taken. The plastic deformation of the aluminium substrate was quantified in terms of maximum residual dent depth. The damage in the composite was quantified in terms of projected damage area by using a histogram based segmentation process within the CFRP layer.

Figure 4 shows the maximum dent depth measured in the aluminium substrate versus the peak indentor displacement and peak force. Both plots demonstrate a linear progression of aluminium dent depth above a threshold value throughout the loading steps/impact levels that were measured. When compared based on peak displacement QSI and LVI shows a strong correlation. When compared on a peak force basis there is a consistent discrepancy between QSI and LVI, indicating a higher peak force is required to achieve the same depth of dent in the aluminium in the LVI case. It can also be noted from Figure 4 that the aluminium substrate has not plastically deformed in the lowest impact energy case whereas both QSI samples did at the lowest load step. A residual deformation of 0.2mm was measured in both QSI samples whereas no evidence of deformation was present in the LVI specimen, indicating a slightly higher threshold value under the LVI regime.

Figure 5 shows the projected area of composite damage in the CFRP layer versus the peak indentor displacement and peak force. Both plots demonstrate a linear progression of the delaminated area in the composite above a threshold value. No damage area was identifiable using the histogram based segmentation and projected area technique in the lowest load/impact specimens. However, detailed assessment of the raw scan data revealed that some intra-laminar micro cracking had occurred in both QSI specimens but not in the LVI case.

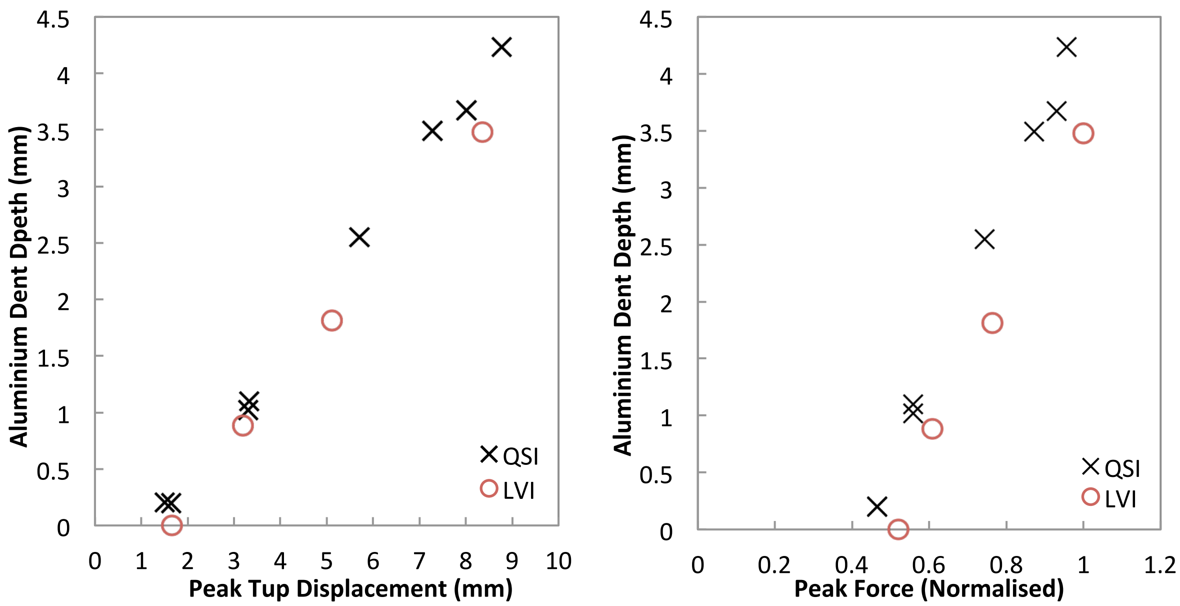

Figure 4. Comparison of the residual dent depth in the aluminium substrate in a HCMS under quasi-static indentation and low velocity impact loading regimes plotted in terms of the peak indentor displacement and the normalised peak force.

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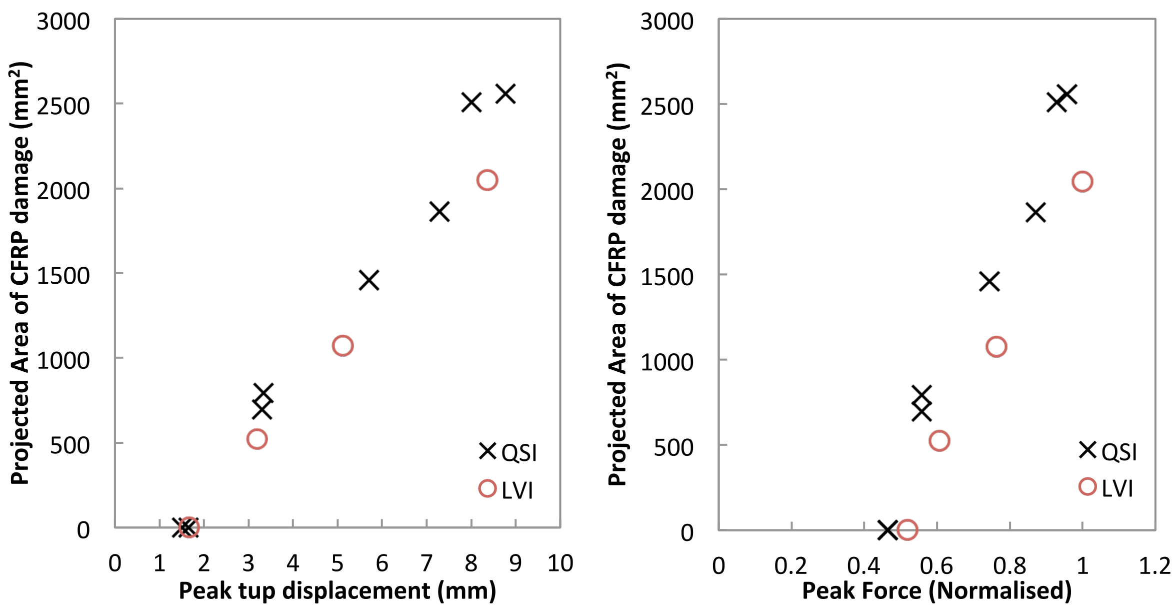

Figure 5. Comparison of the projected area of composite damage in the CFRP layer in a HCMS under quasi-static indentation and low velocity impact loading regimes plotted in terms of the peak indentor displacement and the normalised peak force.

4. Discussion

In general the results demonstrate a strong equivalence between QSI and LVI loading regimes both in terms of force-displacement and the resulting damage response. Nevertheless, some secondary differences were observed. The comparison of the lowest energy impact scan to the lowest load QSI specimens indicates that the threshold value for the initiation of plastic deformation of the aluminium and the onset of CFRP damage is higher under LVI conditions. Both QSI samples demonstrated the onset of damage at a lower load/displacement than the corresponding LVI cylinder in which no evidence of damage was present. However, with only a single specimen CT scanned at the lowest impact level it is difficult to make a definitive conclusion that the damage initiation threshold is higher under LVI conditions or if the observed differences are a result of variability between specimens.

Following the initiation of damage both the dent depth in the aluminium substrate and the projected area of CFRP damage showed a strong equivalence between QSI and LVI testing. The correspondence between loading regimes was closer when compared based on the peak indentor displacement rather than the peak force. This suggests that in future QSI testing using load control conditions would provide a more accurate simulation of LVI conditions. The frame compliance correction factor applied to the QSI data should mitigate the differences in the location of the displacement measurement of the two test machines. However, a possible explanation of the observed differences in peak force versus peak displacement plotted in Figure 2 is that the peak force measurement may be influenced by the oscillatory response of the force signal which may contain ringing artefacts from the dynamic test which are not present under quasi-static load rates.

The interrupted QSI test used in this study reduces the effects of specimen-to-specimen variability but presents an opportunity for low cycle fatigue loading issues to affect the results. The force-displacement response of the QSI results demonstrate that the reloading curve returns to the previous level, or to close proximity, (Figure 1) which is indicative that any low cycle fatigue effect is not affecting the results. However, the damage response described in Figure 5 shows a similar but consistently slightly larger damage area in the QSI case. If low cycle fatigue effects were affecting the response of the structure it would be expected that this would manifest as a slightly larger damage area

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versus a continually loaded sample. Testing of samples at the higher load levels using a continually loaded QSI test would be required to answer this question.

The linear progression of delaminated area above a threshold value seen in this study has been observed in many previous studies of CFRP plates e.g. [5]. This indicates that despite the differences in the geometry and the presence of multiple materials in HCMS the CFRP impact damage response is similar in nature to that of a plate specimen.

5. Conclusion

In this paper the equivalence of QSI and LVI loading regimes on HCMS has been assessed using μCT for subsurface damage assessment. The instrumented force-displacement response of the structures tested showed that under LVI the measured peak force was consistently 10% higher than equivalent QSI test, however the overall response under QSI and LVI was similar. Qualitative assessment of the damage in the most highly loaded samples indicate some differences between the two loading regimes as evidenced by a larger local indent on the surface of the specimen and larger crack opening displacements. Quantitative assessment of two major subsurface damage mechanisms of projected delaminated area and the residual dent depth in the aluminium substrate demonstrated a high degree of equivalence when assessed in terms of peak displacement. Both damage mechanisms demonstrate a linear progression with increasing indentor displacement above a threshold value. There is some evidence from the results to suggest that the damage initiation threshold value is higher under LVI conditions but due to the number of samples tested this cannot be concluded with certainty and would require further testing.

This research indicates that QSI testing can be used as an analogue for LVI in HCMS both in terms of force-displacement and the damage developed in the different material systems above the threshold of damage initiation This conclusion has implications for future impact research studies and finite element modeling of impact events on HCMS.

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