Effects of transient dynamic loading on the energy absorption capability of composite bolted joints undergoing extended bearing failure

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Abstract

Carbon fibre reinforced polymer (CFRP) materials are widely used in transport aircraft. Crashworthiness requirements demand sufficient energy absorption capacity, especially in the fuselage structure. In a recently-proposed approach, specifically-designed “tension absorber” joints utilize tension loads for energy absorption via progressive bearing failure. For further development of the concept, experimental tests are performed on pin-joints in quasi-isotropic CFRP material, under transient dynamic loading at 3 m/s. Investigated parameters are laminate thickness, stacking sequence and pin diameter, and the results are evaluated using the performance parameters ultimate bearing strength, mean crush stress and mass-specific energy absorption. A strong relation between the ratio of pin diameter to laminate thickness, \(D/t\), and the performance parameters is found. Compared to previous results for quasi-static loading, the ultimate bearing strength is increased whereas the mean crush stress and mass-specific energy absorption are reduced. Digital image correlation and computed tomography analysis reveals the mechanisms behind the observed trends. The results provide a basis for further optimization of energy-absorbing joints and validation of finite element models.

Keywords:
Composite bolted joints, high strain-rate testing, energy absorption, progressive bearing failure

1. Introduction

Carbon fibre reinforced polymer (CFRP) composites are widely used in commercial transport aircraft such as the Airbus A350 and Boeing B787. Crashworthiness requirements demand sufficient energy absorption capacity, especially in the fuselage structure, to ensure an acceptable level of occupant safety in survivable impact events [1, 2]. The generally brittle failure behaviour of CFRP composites necessitates specific crash concepts and energy absorbing devices in areas of the fuselage where substantial damage is expected in a crash event. Wide-body transport aircraft provide dimensions that enable absorption of a large portion of the crash kinetic energy by crushing of the sub-cargo floor structure [3]. Narrow-body aircraft however provide less available crush distance in this area of the fuselage, so further energy absorption concepts are required. Various
Ideas have been developed based on the different load types acting in different parts of the fuselage, for example devices designed to exploit bending loads in the frames [4], or compression loads in sub-floor beams [5-7].

Devices also can be designed to absorb energy under tensile loading, an idea previously implemented for aircraft cabin overhead luggage bins [8]. Recently, Airbus and DLR [9] have developed concepts for using such “tension-absorbers” in aircraft fuselages, as illustrated in Figure 1(a). Tension loads that act in a crash scenario in the cargo crossbeam, or the bolted connection between the passenger crossbeam and frame, are used to absorb energy in a controlled manner by progressive bearing failure. Predictions from full-scale simulations showed that up to 50% of the overall absorbed energy could be absorbed by such tension-absorbers [10].

Composite bolted joints are typically designed to fail in bearing and not in catastrophic failure modes such as shear out or net tension. In bearing failure, energy is absorbed by crushing of material in front of the bolt. In a severe loading, the energy absorption of standard joints is limited due to the interruption of the crushing process by bolt pull-through failure. The complex failure of composite bolted joints has been extensively studied in the past, both experimentally and numerically [11-15].

In tension-absorbing joints, high energy absorption is achieved by sustaining the bearing failure process over much longer distances. To prevent pull-through failure, specially designed washers and notches are used, as shown in Figure 1(b). Airbus and DLR have undertaken experimental and numerical studies of this concept using single- and multi-bolt coupons and structural elements [9, 10, 16]. Further studies on the effects of individual material and geometric parameters considered a simplified design where a pin is pulled through a composite plate. The pin-loaded setup has been used in [17, 18] to study the energy-absorbing performance of a wide variety of fibre and matrix materials, fibre architectures and layups, under quasi-static ($3.3 \times 10^{-3}$ m/s) and high-rate loading (3 m/s). It has also been used to study the influence of loading rate on the bearing response of a carbon/epoxy laminate in [14]. As loading rate increased from $10^{-4}$ m/s to 1 m/s, the peak bearing load increased by more than 20% and the steady-state load plateau decreased by more than 60% [14].

In a European Commission funded research project, DLR and the University of Limerick (ULIM) are collaborating to extend the studies on tension absorbers in [10, 14, 16-18]. In the present work, the effects of geometric and material parameters on bearing strength and energy absorption at dynamic loading rates are studied. Bearing strength is relevant since joints designed for tension absorption must primarily withstand operational loads. Fifteen configurations, involving variations in pin diameter, laminate thickness and stacking sequence are tested at a loading rate of 3 m/s. The loading rate of 3 m/s is in the range of expected tensile
loading rates at the cabin cross beam attachment for typical transport aircraft crash events [19]. It is also the same as in [17, 18] on other materials. Comparisons are made with results from quasi-static (1.67 \times 10^{-4} \text{ m/s}) loading in [20] using the same test setup. The chosen material system is HexPly® IM7/8552 which has been used in the third world-wide failure exercise [21]. All parameters needed to calibrate numerical models for this material are already available [22-24]. The test campaign was split between the laboratories at DLR and ULIM.

2. Materials and Methods

2.1 Specimen and test campaign details
The material system used is IM7/8552 (EU version: 134 gsm) with a nominal ply thickness of 0.125 mm. Quasi-isotropic panels were laid up by hand and consolidated in the ULIM LBBC Technologies TC 1000 THPT autoclave according to the manufacturer specifications. The specimen geometry, shown in Figure 2, is the same as in the quasi-static test programme reported in [20]. As outlined in Table 1, fifteen configurations were tested, involving three pin diameters (4 mm, 8 mm and 12 mm), three laminate thicknesses (1 mm, 2 mm, 3 mm) and two different stacking sequences. The configuration code in Table 1 indicates the laminate stacking sequence, pin diameter and laminate thickness. For the 2 mm and 3 mm thick specimens, the stacking sequences are labelled “dispersed” (DS_) or “blocked” (BK_). Dispersed laminates employ “sub-laminate scaling” [25], having stacking sequences $[45/-45/90/0]_n$, where $n$ is variable. Blocked laminates implement “ply-level scaling” [25], having stacking sequences $[45_m/-45_m/90_m/0_m]$, where $m$ is variable. The 1 mm thick laminates are not labelled DS_ or BK_ as they can be considered as the root stacking sequence for variable $n$ or variable $m$. The $D/t$ ratio for each configuration is given in Table 1 for reference later. Four repeats of each configuration were performed, two at ULIM and two at DLR. The total number of dynamic tests is 60.

![Figure 2: Specimen geometry](image)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Code</th>
<th>Stacking sequence</th>
<th>Pin diameter, $D$ (mm)</th>
<th>Thickness, $t$ (mm)</th>
<th>$D/t$</th>
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</thead>
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<tr>
<td>1</td>
<td>D4_T1</td>
<td>$[45/-45/90/0]_4$</td>
<td>4</td>
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<td>4</td>
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<tr>
<td>2</td>
<td>D8_T1</td>
<td>$[45/-45/90/0]_8$</td>
<td>8</td>
<td>1</td>
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<td>D12_T1</td>
<td>$[45/-45/90/0]_{12}$</td>
<td>12</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>4</td>
<td>DS_D4_T2</td>
<td>$[45/-45/90/0]_{24}$</td>
<td>4</td>
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<td>2</td>
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<tr>
<td>5</td>
<td>DS_D8_T2</td>
<td>$[45/-45/90/0]_{28}$</td>
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<td>2</td>
<td>4</td>
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<tr>
<td>6</td>
<td>DS_D12_T2</td>
<td>$[45/-45/90/0]_{28}$</td>
<td>12</td>
<td>2</td>
<td>6</td>
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<tr>
<td>7</td>
<td>BK_D4_T2</td>
<td>$[45_2/-45_2/90_2/0_2]_4$</td>
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<td>2</td>
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<td>8</td>
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<td>9</td>
<td>BK_D12_T2</td>
<td>$[45_2/-45_2/90_2/0_2]_{12}$</td>
<td>12</td>
<td>2</td>
<td>6</td>
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</table>
2.2 Experimental set-up

Servo-hydraulic test machines were used, an Instron VHS100/20M at DLR and a Zwick HTM 5020 at ULIM. Figure 3 shows the test setup. Specially designed tension rods were used to load the specimen. In contrast to the quasi-static tests in [20], the tension rods were equipped with a stiffener bar to increase the tension rod natural frequencies, and reduce lateral vibration of the arms. The composite specimen was gripped at the fixed end of the test machine and the tension rods were connected via a slack adapter to the loading end. In both facilities, piezo-electric load cells were used to measure the forces. In the DLR setup, strain gauges were glued on both tension rods, as shown in Figure 3, to enable strain-based force measurement close to the pin, to capture transient dynamic effects. However, use of this strain-based force signal is limited to a qualitative measurement as non-linear effects in the gauge calibration prevented quantitatively precise measurements.

The specimen was carefully centred between the tension rods, and variable thickness spacers were used to ensure a gap of 8 mm between the tension rods, regardless of specimen thickness, to allow for unhindered debris outflow. The test velocity was 3 m/s, which is the same as in the dynamic tests of [17, 18]. Observable black dots were marked on the pin and tension rod surfaces for pin displacement measurement using Digital Image Correlation (DIC) software. Specimen surfaces were painted with a speckle pattern for strain field analysis. Detailed information on the data acquisition of both labs is provided in Table 2.
Table 2: Data acquisition details

<table>
<thead>
<tr>
<th>Measurement</th>
<th>DLR</th>
<th>ULIM</th>
</tr>
</thead>
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<td>Force I (load cell)</td>
<td>Piezo-electric, 0 – 200 kN, sampling rate: 96 kHz</td>
<td>Piezo-electric, 0-50 kN, sampling rate: 500 kHz</td>
</tr>
<tr>
<td>Force II (strain-based)</td>
<td>Strain gauges at the tension rods, sampling rate: 96 kHz</td>
<td>-</td>
</tr>
<tr>
<td>Pin displacement (DIC)</td>
<td>GOM Correlate® software, sampling rate: 96 kHz</td>
<td>LaVision DaVis® software, sampling rate: 30 kHz</td>
</tr>
<tr>
<td>Camera</td>
<td>FASTCAM SA-Z, resolution 640×288 pixels, sampling rate: 96,000 fps</td>
<td>FASTCAM SA-1.1, resolution 256×576 pixels, sampling rate: 30,000 fps</td>
</tr>
</tbody>
</table>

3. Results

3.1 Sample force-deflection curves and performance parameter definition

Figure 4 shows sample force-displacement curves for the 2 mm thick specimens (configurations 4-9 in Table 1). Dispersed stacking sequence results are on the left, and blocked stacking sequence results are on the right. Pin diameter increases from top to bottom. Both the quantitatively relevant load cell signal and the qualitative local, strain-based force signal are presented.

As it is typical for dynamic loading, the load cell signal contains oscillations due to system ringing, particularly for the largest diameter pin, as shown in Figure 4(e) and (f). In contrast, the strain gauge signal provides more detail on the pin loading, as this local measurement is less affected by system oscillations. Four main phases which are exemplarily shown in Figure 4(a) can be identified in the strain-based force signal:

**Phase 1:** Increasing load up to a maximum value, $F_{\text{max}}$ at the initial, “primary” peak.
**Phase 2:** Sharp load drop indicating “ultimate bearing failure” followed by a relatively constant load until about 4 - 6 mm.

**Phase 3:** Two or three “secondary” force peaks between about 4 - 14 mm (to be discussed later in section 3.4), followed by the establishment of a stable crushing load which stays fairly constant until about 40 mm.

**Phase 4:** Final failure as the pin pulls through the end of the laminate.

The mean crushing force $F_{\text{mean}}$ is defined here as the average force between 5 mm and 40 mm displacement, to coincide with that used in [20]. To allow comparisons on a material level, the following performance parameters are defined based solely on the unfiltered load cell signals. The ultimate bearing strength (UBS), $\sigma_{\text{ult}}$ is:

$$\sigma_{\text{ult}} = \frac{F_{\text{max}}}{D \cdot t}$$  \hspace{1cm} (1)

where $D$ is the pin diameter and $t$ is the laminate thickness. The mean crushing stress (MCS) is defined as:

$$\sigma_{\text{mean}} = \frac{F_{\text{mean}}}{D \cdot t}$$  \hspace{1cm} (2)

The mass-specific energy absorption (SEA) is defined as the integral of the force–deflection curve divided by the mass of destroyed material. In the pin-bearing tests reported in [17], the destroyed material volume is estimated to be 20% (brittle fibres) to 50% (ductile fibres) larger than the slot volume defined by the pin diameter $D$, the laminate thickness $t$ and the maximum pin displacement $s_m$. To allow comparison with [17], a factor of 1.2 is used here, i.e.:

$$\text{SEA} = \frac{1}{m_{\text{absorbed}}} \int_0^{s_m} F \cdot ds = \frac{1}{1.2 \rho t D s_m} \int_0^{s_m} F \cdot ds$$  \hspace{1cm} (3)

where $\rho$ is the material density and $s_m$ is the considered maximum pin displacement of 40 mm. To compare the results with other studies, the SEA values can be scaled by changing the factor of 1.2 in equation (3).
3.2 Performance parameter results

Figure 5 summarises all the test findings on the variation of UBS, MCS and SEA with pin diameter, laminate thickness and stacking sequence. The results of all four repeat tests, two performed at DLR and two at ULIM, are included. Quasi-static (10 mm/min or $1.67 \times 10^{-3}$ m/s) test results, described in detail in [20], are also shown for comparison. Results for dispersed laminates are presented on the left in Figure 5(a), (c) and (e) while those for blocked laminates are shown on the right in Figure 5(b), (d) and (f). Results for the 1 mm thick specimens are included in both the dispersed and blocked graphs, as the 1 mm laminate can be considered as the root stacking sequence for the dispersed and blocked laminates.
Figure 5: Summary of performance parameter results, (a) UBS dispersed stacking sequence, (b) UBS blocked stacking sequence, (c) MCS dispersed stacking sequence, (d) MCS blocked stacking sequence, (e) SEA dispersed stacking sequence, (f) SEA blocked stacking sequence. Dynamic (3 m/s) results shaded red, quasi-static (1.67×10⁻³ m/s) results shaded grey.

The dynamic UBS values in Figure 5(a) and (b) range between 437 MPa and 900 MPa, and high standard deviations are visible for some configurations. These standard deviations are the result of combining data obtained from the two test setups at DLR and ULIM. MCS, Figure 5(c) and (d), varies between 122 MPa and 284 MPa. SEA, Figure 5(e) and (f), varies between 67 kJ/kg and 147 kJ/kg. The standard deviations for MCS and SEA are moderate, showing that the two test setups at DLR and ULIM only have minor influence on these results and good repeatability of the tests could be achieved. The MCS and SEA values are in the same range as determined in pin bearing tests for a number of fabric, woven and unidirectional carbon fibre composites tested under dynamic loading in [17].

The following observations can be made for the effect of pin diameter under dynamic loading:
(i) UBS generally decreases with increasing pin diameter. D12_T1 and DS_D8_T2 are outliers since the UBS of D12_1 is greater than that of D8_T1 and the UBS of DS_D8_T2 is greater than that of DS_D4_T2.

(ii) MCS decreases with increasing pin diameter. The effect is strongest for blocked stacking sequences.

(iii) SEA decreases with increasing pin diameter. The effect is slightly stronger for blocked laminates.

Summarising the effect of pin diameter under dynamic loading, gives the first main result:

**Main result 1:** With increasing pin diameter, UBS, MCS and SEA generally reduce for all three thicknesses and both stacking sequences.

Next, the *effect of laminate thickness* under dynamic loading is examined:

(iv) UBS increases for increasing laminate thickness. The effect is more pronounced for dispersed laminates, and the increase is larger for a thickness change from 1 to 2 mm, than for a change from 2 to 3 mm.

(v) MCS increases with increasing laminate thickness, with the effect being more pronounced for a thickness change from 1 to 2 mm, than for a change from 2 to 3 mm. DS_D12_T3 is a slight outlier in that its MCS is less than DS_D12_T2, but the decrease is not statistically significant.

(vi) SEA increases with increasing laminate thickness, with again, the effect being most pronounced for a thickness increase from 1 mm to 2 mm.

Summarising the effects of laminate thickness in dynamic loading:

**Main result 2:** UBS, MCS and SEA increase with increasing laminate thickness.

Concerning the *effect of stacking sequence* under dynamic loading (1 mm laminates are ignored here):

(vii) UBS is higher for dispersed stacking sequences than for blocked stacking sequences.

(viii) For 2 mm thick specimens, MCS is higher for dispersed laminates, while for 3 mm specimens, MCS is higher for blocked laminates (apart from DS_D12_T3 and BK_D12_T3 which have about the same MCS).

(ix) The trends for SEA are essentially the same as for MCS.

Summarising the effect of stacking sequence under dynamic loading:

**Main result 3:** Laminates with dispersed stacking sequences have significantly higher UBS than those with blocked stacking sequences. The variations in MCS and SEA with stacking sequence are less consistent, and relatively small.

Finally, the *effect of dynamic loading* is described:
(x) UBS is significantly higher under dynamic loading than quasi-static loading. The trends seen under quasi-static loading remain unchanged under dynamic loading, i.e. UBS decreases as the pin diameter increases, increases as laminate thickness increases and is higher for dispersed stacking sequences.

(xi) MCS is lower under dynamic loading than quasi-static loading. At both loading rates, MCS decreases as pin diameter increases and increases as thickness increases. At quasi-static loading rates, MCS is highest for blocked laminates with 4 mm pins, and highest for dispersed laminates with 8 mm and 12 mm pins. Under dynamic loading the trends are less clear.

(xii) SEA is lower under dynamic loading than quasi-static loading (with the exception of D12_T1 for which no difference is evident). At both loading rates, SEA decreases as pin diameter increases, and increases with increasing thickness. Regarding stacking sequence, the comments in (xi) above for MCS also apply to SEA.

Summarising the effect of dynamic loading:

**Main result 4:** Increasing the loading rate from $1.67 \times 10^{-3}$ m/s to 3 m/s results in an increase in UBS, and a decrease in MCS and SEA for all pin diameters, laminate thicknesses and stacking sequences.

**Main result 5:** The effects of pin diameter, laminate thickness and stacking sequence on the performance parameters do not change significantly with loading rate. For the given test conditions and range of investigated parameters, using quasi-static tests for parameter studies on tension-absorbing joints appears to be a valid approach if dynamic test equipment is not available.

### 3.3 Performance Parameters versus $D/t$ ratio

Under quasi-static loading, [20], the performance parameters showed a strong correlation with the ratio of pin diameter to laminate thickness, $D/t$. Figure 6 plots UBS, MCS and SEA versus $D/t$ for dynamic loading, with quasi-static results from [20] included for comparison. Again, the results of all four repeat tests of each configuration are considered but the error bars are omitted for clarity. The data for UBS, Figure 6(a), are separated into two well-defined groups for quasi-static and dynamic loading. Under dynamic loading, the dispersed stacking sequence data can be fitted with a power law with an $R^2$ value of 0.68. For blocked laminates, the $R^2$ value is 0.84. The difference in UBS for the two stacking sequences is much larger at low $D/t$ than at high $D/t$, for both loading rates. Likewise the differences due to loading rate are most pronounced at low $D/t$.

MCS, Figure 6(b), shows a strong correlation with $D/t$, for dispersed and blocked stacking sequences, at dynamic loading rates. In fact the correlation is just as strong as for quasi-static loading. For dispersed laminates, a power law can be fitted to the dynamic data with an $R^2$ value of 0.93, while for blocked laminates,
an $R^2$ value of 0.96 is obtained. When the dynamic data for both stacking sequences are combined, a single power law with an $R^2$ value of 0.93 can be fitted, reflecting the relatively small effect of stacking sequence on MCS seen above. SEA shows similar trends, Figure 6(c). For dispersed stacking sequences, SEA versus $D/t$ can be fitted by a power law with an $R^2$ value of 0.93 and for blocked laminates an $R^2$ of 0.92 is obtained. When both stacking sequences are grouped together, a fit can be made with an $R^2$ value of 0.91. As for UBS, the effect of loading rate on MCS and SEA is most pronounced at low $D/t$.

Summarising these observations, the following conclusion can be made:

**Main result 6:** The performance parameters show similar correlations with $D/t$ under quasi-static and dynamic loading. For dynamic UBS, MCS and SEA, the effect of loading rate is strongest at low $D/t$. MCS and SEA, which are most relevant for energy absorption, show a strong correlation with $D/t$ for both loading rates.

![Figure 6: Performance parameters versus the $D/t$ ratio. (a) UBS (b) MCS (c) SEA](image)

### 3.4 Strain gauge results and 2D DIC

As noted in section 3.1, Figure 4, following the initial, primary force peak, two or three secondary force peaks are visible in the strain gauge data between 4 and 14 mm pin displacement. No secondary peaks were reported for the quasi-static tests in [20]. To investigate this, 2D DIC was used to measure full-field surface strains. In the DIC software GOM Correlate®, facets with size 16 x 16 pixel$^2$ and 2 pixel distance of the facet centres were used to resolve the surface speckle pattern resulting in a spatial resolution of 0.1 mm per pixel.
Figure 7 shows the DIC analysis of the 2 mm thick laminates. Dispersed laminates are shown on the left and blocked laminates on the right. The analysis is performed at a pin displacement of 0.75 mm, which is about 0.3 mm after the primary load peak. The strain field measurement is used here for qualitative evaluation of the spread of damage in front of the pin. The dashed lines indicate splits on the surface which formed after the primary force peak. Additionally, the force-deflection curve based on strain gauge data is shown. Distances between the displacement corresponding to the DIC images (0.75 mm) and the displacement of the first secondary peak are shown. The distances range from 3.7 mm to 5.2 mm. These distances are also shown on the DIC images. It can be seen in Figure 7 that the highest compressive strains and splits are within this distance. Furthermore, referring back to Figure 4, it can also be seen that the mean load level between the primary and first secondary force peak is lower than the steady-state load of the progressive bearing process (i.e. between about 15 and 45 mm pin displacement), especially for 12 mm pin diameter in Figure 4(e) and (f). We conclude that the displacement at which the first secondary peak occurs indicates the initial damage spread at bearing failure initiation (i.e. the primary force peak). Following bearing failure, the pin travels through a damaged region resulting in reduced resistance. This damage state remains nearly constant until the pin reaches the end of the damaged region, indicated by the first secondary force peak. Afterwards, the process repeats and finally results in steady-state, progressive bearing, characterised by constant damage growth and constant load level.
Figure 7: Force-displacement plots up to 10 mm pin displacement and 2D DIC strain field analysis at a pin
displacement of 0.75 mm, (a) DS_D4_T2; (b) BK_D4_T2; (c) DS_D8_T2; (d) BK_D8_T2; (e) DS_D12_T2; (f)
BK_D12_T2 (continued on next page).
Figure 7 (continued): Force-displacement plots up to 10 mm pin displacement and 2D DIC strain field analysis at a pin displacement of 0.75 mm. (a) DS_D4_T2; (b) BK_D4_T2; (c) DS_D8_T2; (d) BK_D8_T2; (e) DS_D12_T2; (f) BK_D12_T2
3.5 Post-test appearance and 3D CT analysis

Figure 8 shows the post-test appearance of one sample of each configuration. It can be seen that damage in the unsupported surface plies partly extends to the specimen edge with large strips of the outer 45° plies peeled off, particularly for blocked laminates. A closer look reveals that the peeled off blocks contain two 45° plies for 2 mm thick laminates, and three 45° plies for 3 mm thick laminates, whereas for dispersed laminates, only one surface ply is peeled off. The energy absorbed by peeling is low and a large number of peeled off surface plies is detrimental to energy absorption. However, stacking sequence showed just a small influence on SEA in Figure 5(e) and (f), indicating that the number of surface plies involved in peeling has minimal influence on energy absorption. Compared to the post-test appearance of the quasi-static tests presented in [20], peeling is more prominent for quasi-static loading than for dynamic loading.

To examine the internal damage state, post-test three-dimensional computed tomography (3D CT) scans were conducted using a high resolution µCT-System v|tome|x L240/450 by phoenix|x-ray. Figure 9 shows the 20×20 mm² field scanned with a voxel resolution of 12 µm. The µCT data were analysed with the commercial software package VGStudioMax 3.2 (Volume Graphics, Heidelberg). The scans were performed on the configuration with 2 mm laminate thickness, and 4 mm and 8 mm diameter pins. The 12 mm diameter pins were omitted in the CT-analysis since the full extent of the lateral damage could not be captured within the 20×20 mm² field scanned using the favoured voxel resolution of 12 µm.
Also shown in Figure 9 is the cross-section, 14 mm from the hole edge, chosen as the section view for the following figures. Steady-state, progressive crushing had been established by the time the pin reached this cross-section. As noted in the figure, the region of the laminate through which the pin travels will be referred to here as the “bearing notch”.

Figure 9: Field of view for post-test 3D CT-scans and position of section view shown in Figure 10.

Figure 10 shows the aforementioned section view for DS_D4_T2, DS_D8_T2, BK_D4_T2 and BK_D8_T2. Plies are colour-coded and blue lines indicate 90° changes in fibre orientation. MCS and SEA values are indicated, and the dashed box represents the pin. For dispersed laminates, Figure 10(a), (b), three to six delaminations are clearly visible, which spread far into the laminate on either side of the bearing notch. Most delaminations are between interfaces with a 90° change in orientation. As indicated in Figure 10, the maximum delamination width (distance between furthest extent of delamination on left and right of the bearing notch) was found to be about 2.5D for the 4 mm pin and 1.9D for the 8 mm pin, where D is the pin diameter. These values were approximately constant over the length of the scanned region. However, the width of the main fibre/matrix fragmentation damage is less. For the 4 mm diameter pin, the width of fragmentation damage ranges from about 1.0D in the central plies up to 2.0D in the unsupported surface 45° plies. For the 8 mm pin, the width of fragmentation damage is about 1.0D in the centre plies and 1.8D in the peeled-off surface 45° plies.

For blocked laminates, Figure 10 (c), (d), distinctive delaminations are visible mainly at the four ply interfaces involving a 90° change in fibre orientation. Larger debris wedges are visible, compared to the dispersed laminates, which force the delamination damage further into the laminate. The delamination width reaches about 3.6D and 2.1D for the 4 mm and 8 mm pins, respectively. Peeling of the surface plies is more obvious for the blocked laminates with large pieces of the two outer 45° plies missing. Blocks with similarly oriented plies are clearly identifiable. The width of fragmentation damage is highest in the -45° plies, reaching
about 2.8D and 1.9D for the 4 mm and 8 mm pins, respectively. Again, the width of both delamination and fragmentation damage was found to be about constant over the length of the scanned region.

(a) DS_D4_T2 dynamic loading

(b) DS_D8_T2 dynamic loading

(c) BK_D4_T2 dynamic loading
Figure 10: Post-test CT-scan section views at a position 14 mm in front of the initial pin position (see Figure 9). View is in pin loading direction. (a) DS_D4_T2; (b) BK_D4_T2; (c) DS_D8_T2; (d) BK_D8_T2

Two specimens tested under quasi-static loading were also scanned for comparison. Figure 11 shows configurations with 2 mm laminate thickness and 4 mm pin diameter. Comparing the damage state for both loading rates, Figure 10(a), (c) versus Figure 11(a), (b), we first discuss the damage outside (i.e. to the left and right of) the bearing notch. For the dispersed laminate in Figure 11(a), six delaminations are visible and the delamination width is about $3.0D$. In comparison, the dynamically tested specimen, Figure 10(a), had the same number of delaminations but the delamination width was less ($2.5D$). The same trend can be identified for the blocked laminate, Figure 10(b) versus Figure 11(b). Again, the number of delaminations is the same (four), but the delamination width is higher for quasi-static loading ($4.3D$) than for dynamic loading ($3.6D$).
Turning to the damage within the bearing notch, significant differences are seen for the two loading rates. For both stacking sequences, under quasi-static loading, debris is visible within the bearing notch (i.e. within the dashed lines representing the pin), Figure 11(a) and (b). Some of the debris is clearly still connected to the laminate on either side of the bearing notch. In particular, in the ±45° plies, fibres have bent and broken but the broken portions of the ply have not always fully detached. As this is only a two-dimensional slice, debris which looks disconnected from the surrounding material in the images may actually be connected at another cross-section (and probably is, or it would most likely have fallen out during handling of the specimen for CT analysis). The debris is more evident for the dispersed laminate, Figure 11(a), due to the even distribution of the ±45° plies in the laminate. In contrast, the specimens tested under dynamic loading, Figure 10(a) and (c), show much less debris within the bearing notch, indicating the pin has made a clean cut through the laminate, including the ±45° plies, and consequently most of the debris has been ejected from the bearing notch.

4 Discussion

As noted in section 3.2, (main result 5), the effects of pin diameter, laminate thickness and stacking sequence (main results 1-3) on the performance parameters do not change significantly as the loading rate increases from quasi-static (1.67×10^{-4} m/s) to dynamic (3 m/s). The causes of those effects were explained in [19], via CT scans of quasi-static tests, interrupted at 0.75 mm (just past the peak load). It was not possible to perform interrupted dynamic tests but, as the trends have been found here to be the same, we assume that the main causes for the trends are similar to those for quasi-static loading. Hence, for explanations of main results 1-3, we refer the reader to [19], and focus here on the differences between quasi-static and dynamic loading, and the significance of the new information obtained for dynamic loading.
Main result 4 states that increasing the loading rate from $1.67 \times 10^{-4} \text{ m/s}$ to 3 m/s results in an increase in UBS and a decrease in MCS and SEA for all pin diameters, laminate thicknesses and stacking sequences. The increase in UBS is between 23% for D8_T1 and 74% for BK_D8_T3. In [14], an increase of the peak bearing load of about 20% was reported when the loading rate was increased from $8.3 \times 10^{-5} \text{ m/s}$ to 1 m/s. This is less than the upper range of increases seen here, but the highest loading rate here is 3 m/s compared to 1 m/s in [14], and the material and geometry in [14] were different also (Hexply M21/35%/268/T700GC, 4 mm thick laminates, 6.35 mm pins).

The increase in UBS from quasi-static to dynamic loading observed here can be explained by the strain rate dependent material properties of the composite material system, IM7/8552. A change from quasi-static to dynamic loading has been reported to lead to an increase of 40% in fibre compressive strength [24], and 63% in fibre fracture toughness [23]. In addition, an increase of 45% in matrix-dominated transverse compression strength, and increases of 42% in both in-plane shear strength and combined transverse compression/in-plane shear strength [22] have also been reported. Consequently, under dynamic loading, both the matrix and the fibres provide greater resistance to fibre kinking, which is the main failure event at bearing failure.

Regarding MCS, the reduction from quasi-static to dynamic loading ranges from 10% for D12_T1 to 29% for BK_D4_T2. This is in line with results from the literature where reductions of 20-40% [17, 18] and 60% [14] have been reported. For SEA, the reduction from quasi-static to dynamic loading ranges from 0% for D12_T1 to 26% for BK_D4_T2. A reduction in SEA was also reported for pin bearing tests in [17, 18] and is in line with data on other composite structures subjected to crushing in [26, 27].

In [14], infrared thermography was used to estimate the width of the damaged area in pin-bearing tests. It was found that the width decreased as the loading rate increased, and it was concluded that this was why the MCS reduced at higher loading rates. Here, using a different method (3D CT), a similar result is found concerning the width of the damaged area. As presented in section 3.5, Figure 10 and Figure 11, the maximum delamination width is lower for dynamic loading than for quasi-static loading, for both stacking sequences. In other words, the damage extends deeper into the laminate on either side of the bearing notch, under quasi-static loading, increasing the overall energy absorbed by the material. Another factor likely to affect MCS and SEA is friction. In section 3.5, Figure 10 and Figure 11, it was identified that under dynamic loading, the pin makes a relatively clean cut through all the plies, and debris is thus ejected from the bearing notch ahead of the pin. However, under quasi-static loading, large strands of material are evident within the bearing notch of the post-test specimens (see Figure 11). This material, still having some bending stiffness due to its connection with the
surrounding material, provides increased frictional resistance to the motion of the pin, under quasi-static loading. A similar effect has also been identified for crushing of composite structures under both quasi-static and dynamic loading in [27].

As summarised in main result 6, the finding in [20] that the performance parameters, UBS, MCS and SEA are strongly correlated with \(D/t\) ratio, for quasi-static loading, turns out to be also true for dynamic loading. In particular, for MCS and SEA, single power laws applicable to both stacking sequences, can be fit to the data with \(R^2\) values of 0.93 and 0.91 respectively. Hence, the graphs in Figure 6 can be used to derive design criteria for bolted connections with regard to optimum strength and optimal energy absorption depending on the \(D/t\) ratio. In addition, the influence of design parameters under different loading rates becomes obvious.

As a final observation, recall that in the definition of SEA in Eq. (3), the width of destroyed material was defined to be \(1.2D\) where \(D\) is the pin diameter, based on the definition in [17]. In [20] it was suggested that a width of \(2D\) might be more appropriate based on CT-scans of quasi-statically tested specimens. Here, the CT-scans of dynamically loaded specimens in section 3.5 illustrate the difficulty of determining a definitive value. The maximum delamination width is up to \(3.6D\) but the contribution of delamination to the energy absorption is relatively low so taking this definition would result in too low SEA values. The width of \(1.2D\) in [17] was defined based on micrographs of fabric materials where distinct lateral delamination could not be identified. Considering fragmentation damage as the main energy absorbing mode, the width of destroyed material for the current dynamically loaded specimens, is between \(1D\) and \(1.75D\) (Figure 11) depending on the fibre orientation and position in the stacking sequence. Overall, this just illustrates the difficulty in defining a single damage width in quasi-isotropic laminates and hence in precisely determining SEA.

5 Conclusions

An extensive experimental study has been performed on extended bearing failure of pin-loaded composite joints under transient dynamic loading, with varying pin diameter, laminate thickness and stacking sequence. The results supplement a previously performed test campaign under quasi-static loading, reported in [19]. The main findings are:

i. The effects of pin diameter, laminate thickness and stacking sequence on the performance parameters do not change significantly with loading rate. For the given test conditions and range of investigated parameters, using quasi-static tests for parameter studies on tension-absorbing joints appears to be a valid approach if dynamic test equipment is not available.
ii. Increasing the loading rate from $1.67\times10^{-3}$ m/s to 3 m/s results in an increase of 23-74% in UBS, and decreases of 10-29% and 0-26%, in MCS and SEA, respectively.

iii. The increase in UBS is attributed to the strain-rate dependent properties of IM7/8552. The decreases in MCS and SEA correlate with a decrease in width of damaged material and a decrease in debris in the bearing notch, under dynamic loading, both determined from 3D CT. The extra debris under quasi-static loading, still attached to the surrounding material, increases the frictional resistance to pin travel.

iv. The performance parameters, UBS, MCS and SEA show strong correlations with $D/t$ ratio under dynamic loading, a result previously shown in [20] for quasi-static loading. In Figure 6, the influence of design parameters under different loading rates is compactly summarised, and the relationships shown can be used to derive design criteria for bolted connections with regard to optimum strength and/or energy absorption.

v. Small pin diameters and dispersed stacking sequences provide the highest energy absorption and also the highest bearing strength.

vi. The reason why the load is lower just after the peak load, than it is later on, has been found, via DIC combined with strain-gauge force measurements, to be due to a sudden growth of damage at bearing failure to a distance about 5 mm in front of the pin. The load is low as the pin travels through this damaged region, but then rises up and produces a secondary peak (visible only in the strain gauge data) at the end of this region. The process repeats until a stable crush load is established.

The extent to which these findings also apply to anisotropic layups will be examined in future work. The results for dynamic testing in this paper and quasi-static testing in [19] extend the validation basis for potential future work on the numerical simulation of progressive pin bearing failure.

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References:


