AN EFFICIENT ANALYTICAL MODEL OF COMPOSITE BOLTED LAP JOINTS SUBMITTED TO HIGH RATES OF LOADING

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Abstract
An analytical model was developed to efficiently determine the bearing response of composite bolted joints under various rates of loading. The load carried by the bolt was determined via a series of piecewise continuous functions to represent the various states of damage in the joint as a consequence of the applied displacement. The model was compared to experimental data obtained from single-bolt, single-lap joints tested quasi-statically and at rates of 5 m/s and 10 m/s. A good correlation between the model and the experimental results was observed for all test cases considered.

1 Introduction
The use of carbon fibre-reinforced plastic (CFRP) materials in primary aircraft structures has increased significantly in recent decades. This is evident from the latest generation of large commercial aircraft, e.g. the Boeing 787 and Airbus A350XWB, which consist of over 50% composite material by weight. Despite the lower structural efficiency when compared to adhesively bonded joints, bolted joints are still widely used in modern aircraft due to their ease of installation and disassembly, and resistance to environmental degradation. Consequently, due to the large number of mechanical fasteners in modern aircraft, significant weight savings can be realised by optimising the joint design.

There have been numerous studies carried out in the literature on the quasi-static response of mechanically fastened composite joints and as a result the mechanics of this problem are relatively well understood [1-4]. However, as a consequence of the operating environment of aircraft, many of the critical load cases for structural design are impact or crash scenarios which are characterised by high rates of loading. A number of authors have investigated joints loaded at rates comparable to those that may be experienced during a survivable crash situation [5-9]. It was apparent that any rate effects observed are dependent on a number of experimental parameters which appear to include the parent material of the joint, its preparation and layup, and the geometry of the joint: including thickness, clearance, width and end-distance. Additionally, fastener head-type, bolt diameter, bolt pre-load, loading velocity and the loading direction (i.e. bearing or fastener pull-through) also appear to play a crucial role in the rate-sensitivity of the joint.

Ger et al. [5] investigated the effects of loading rate on the structural response of mechanically fastened CFRP and carbon-kevlar fibre reinforced plastic (HFRP) joints. Specimens were tested quasi-statically and dynamically (loading rates of 3-5 m/s). In general it was found that there was a decrease in energy absorption and increase in joint stiffness for the dynamic loading rates. However, inertia effects of the specimen attachment were not accounted for which might have led to unreliable or misleading conclusions. Li et al. [6] tested a number of carbon fiber joint configurations in bearing at loading rates between quasi-static and 8 m/s. The results obtained contradict those from [5]. It was found that for the majority of tested specimens, the stiffness and strength of the joint only increased slightly with loading rate but there was a significant change in failure mode at higher rates (4-8 m/s) which generally resulted in increased energy absorption. Pearce et al. [7] tested a series of joints and structures in bearing and pull-through directions at dynamic rates between 0.1 and 10 m/s. Only minor
loading-rate sensitivities were observed in the pull-through and multi-bolt structural impact tests. Specimens loaded in bearing experienced a pronounced change in failure mode when loaded at or above 1 m/s. Although the failure initiation load and ultimate load did not change with rate, the energy absorption increased significantly. This was owed to a change in residual strength of the specimens’ post ultimate load. Heimbs et al [8] also tested a series of mechanically fastened, carbon/epoxy laminate joints up to loading velocities of 10 m/s. Single-lap shear tests on single-bolt and two-bolt specimens, bolt pull-through tests and coach peel tests were carried out. It was found that only the two-bolt, single-lap shear specimens showed rate dependence where the final failure mode changed from net-tension to extensive bearing and pull-through. This rate-dependent change in failure mode resulted in increased energy absorption of the joint.

A number of single-lap joints with layups representative of aircraft fuselage skin panels were tested by Egan et al. [9] quasi-statically and at 5 m/s and 10 m/s. It was found that the energy absorption for all test cases considered increased with loading rate. For the thinner laminates tested it was found that fastener pull-through was the dominant final failure mode, but for thicker laminates tested the failure mode was found to vary between fastener failure and fastener pull-through. The former resulted in decreased energy absorption due to premature fastener failure. In the thinner laminates it was also found that the ultimate load carried was significantly lower in the dynamic tests. During the testing of these specimens significant heating of the joint was also observed, which may have been a contributing factor to the lower ultimate loads. Reviewing the rate effects observed in [5-9] during joint testing, a common observation is a change in energy absorption of the joint, with most authors reporting an increase. This appears to be a key parameter in predicting the dynamic response of composite bolted joints.

In order to carry out an accurate numerical analysis of a composite bolted joint, the use of expensive three-dimensional finite element (FE) techniques is required if a conventional approach is taken. A model accounting for the most significant characteristics in the joint load-displacement curve must include frictional effects between the laminates and the clamping effect of the bolt. In addition, a complex material model is required to account for damage initiation and progression within the composite material as well as any significant strain-rate effects that may be present. Accounting for these effects in a detailed numerical model significantly lengthens the computational time required for an analysis, thus making further numerical optimisation studies infeasible. An analytical model was developed to determine the response of the single bolt joint in advance of the finite element calculation. The detailed mesh required for the joint area could then be replaced by a simple two-node element whose response is determined by the analytical model. This would allow extremely efficient finite element analyses of large composite structures to be realised. This technique was successfully implemented by Gray and McCarthy [10] for composite joints under quasi-static rates of loading.

2. Experimental Data
Experimental data obtained from Egan et al [9] was used to validate the analytical model developed. A number of single-lap, composite bolted joints were tested quasi-statically and at rates of 5 m/s and 10 m/s. Quasi-static tests were performed on a Zwick 100kN universal hydraulic machine while dynamic tests were carried out on a Zwick Amsler HTM 5020 high-speed testing machine. All joints were manufactured from a carbon fiber composite prepreg with a toughened epoxy resin. Fasteners were aerospace grade titanium alloy (Ti-6Al-4V) 4.8 mm diameter bolts with a 130° countersunk head (ABS0873) and steel nuts (ANSA2536). Figure 1 illustrates the joint geometry. A number of tapered and non-tapered specimens were tested. However it was found that joint response was dictated primarily by the layup in the overlap region [9]. For this reason only non-tapered layups were modelled. The dimensions of the joint and the fibre orientations for the layups considered are given in Tables 1 and 2 respectively.
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Fig. 1. Geometry of single-bolt, single-lap joint specimen tested

Table 1. Dimensions of single-bolt specimen tested

<table>
<thead>
<tr>
<th>g (mm) (QS/HS)</th>
<th>L (mm) (QS/HS)</th>
<th>d (mm)</th>
<th>e (mm)</th>
<th>w (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>75/50</td>
<td>155/160</td>
<td>4.8</td>
<td>15</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 2. Fibre orientations of layups tested

<table>
<thead>
<tr>
<th>Layup</th>
<th>Orientations</th>
<th>t (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>45/90/-45/0/0/-45/0/0/-45/0/0/-45/90/45</td>
<td>2.125</td>
</tr>
<tr>
<td>E</td>
<td>45/90/-45/0/0/-45/0/0/-45/0/0/-45/0/0/-45/90/45</td>
<td>3.125</td>
</tr>
</tbody>
</table>

For every test case considered a minimum of three repeats were carried out and very good repeatability was found for all load cases. A representative sample of the C-laminate tests at various loading rates is shown in Figure 2 to illustrate rate phenomena observed during testing. Results for all test cases are presented in Section 4 where the model is compared with the experimental results.

Fig. 2. Experimental results for C laminate joints tested at quasi-static and dynamic loading rates

Fig. 3. Schematic of characteristic loading curve for single bolt joint

From Figure 2, it can be seen that although the elastic response of the joint appears to be rate independent, the damaged response does not. This is evident through dissimilarities between the first failure loads, $P_{ff}$, ultimate loads carried, $P_{ult}$, and the energy absorption during failure. These differences are illustrated in Figure 3. Furthermore, the damage response appears to consist of an amalgamation of a non-linear region prior to $P_{ult}$ and a quasi-linear region after reaching the ultimate load. This observation will be discussed further in Section 3.2.

It is clear that the energy absorption of the joint is a key variable in predicting its rate response. The energy absorbed during the non-linear and quasi-linear damage regions illustrated in Figures 3 and 7 will be denoted $E_1$ and $E_2$ respectively. These energies, as well as the first and ultimate failure loads, were determined and averaged for each layup and associated loading rates are presented in Tables 3 and 4.

Table 3. C Laminate key damage variables

<table>
<thead>
<tr>
<th>$QS$</th>
<th>$P_{ff}$ (kN)</th>
<th>$P_{ult}$ (kN)</th>
<th>$E_1$ (J)</th>
<th>$E_2$ (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 m/s</td>
<td>5.04</td>
<td>9.2</td>
<td>17.21</td>
<td>4.11</td>
</tr>
<tr>
<td>10 m/s</td>
<td>5.19</td>
<td>7.1</td>
<td>2.96</td>
<td>38.86</td>
</tr>
<tr>
<td>4.74</td>
<td>7.23</td>
<td>4.95</td>
<td>28.64</td>
<td></td>
</tr>
</tbody>
</table>
It is apparent from Figure 2 and Tables 3 and 4 that the majority of energy absorbed during dynamic testing occurs after the ultimate load has been reached i.e. during the quasi-linear unloading regime. This is in contrast to the quasi-static tests where the energy absorbed during the quasi-linear region is almost negligible in comparison to that absorbed during the non-linear damage region. In addition, it appears that $E_2$ varies as a function of the final failure mode. In the joints tested that were manufactured from the E-layup, two final failure modes were present; fastener failure and extensive bearing damage leading to fastener pull-through. It was observed that for the 5 m/s cases fastener pull-through was the dominant failure mode whereas fastener failure was the dominant mode of failure for the 10 m/s cases. In Table 4, the average energies absorbed in cases that failed via the non-dominant failure mode are given in brackets. For the 5 m/s case this was fastener failure while for the 10 m/s case this failure mode was fastener pull-through. It is interesting to note that the energies corresponding to a particular failure mode for the E-layup are very similar regardless of loading rate. Table 5 below gives a complete list of the final failure mode for each test conducted, where FF denotes fastener failure and FP denotes fastener pull-through.

### Table 4. E Laminate key damage variables

<table>
<thead>
<tr>
<th>QS</th>
<th>$P_{ff}$ (kN)</th>
<th>$P_{ab}$ (kN)</th>
<th>$E_1$ (J)</th>
<th>$E_2$ (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 m/s</td>
<td>7.73</td>
<td>9.56</td>
<td>4.07</td>
<td>0.313</td>
</tr>
<tr>
<td>10 m/s</td>
<td>10.00</td>
<td>11.5</td>
<td>2.14</td>
<td>36.4 (11.7)</td>
</tr>
<tr>
<td>8.51</td>
<td>11.6</td>
<td>7.17</td>
<td>15.9 (38.35)</td>
<td></td>
</tr>
</tbody>
</table>

A simple analytical model was developed to predict the load-displacement response in order to accelerate finite element calculation times for bolted joints at various rates of loading. The elastic response was determined by a system of equivalent springs whereas the damaged response was predicted from knowledge of the energy absorption characteristics of the joint as well as the first failure and ultimate loads. But as mentioned in Section 1, there are numerous parameters that influence the rate sensitivity of the joint. It was hoped that the development of a model based primarily on the energy absorption characteristics would provide a simple yet accurate approach to capture the response of the joint at various rates of loading.

### 3.1 Elastic Joint Response Model

It was observed that the elastic response of the joint is composed of two quasi-linear regions arising from the friction between the laminates and the joint stiffness (governed by the properties of the bolt and composite material) [1, 5]. This gives rise to slopes $K_1$ and $K_2$ respectively as shown in Figure 4. A number of authors [4, 11-13] have investigated the problem of predicting the response of bolted joints when loaded within their elastic range. A similar approach to that developed by [4, 11-13] was implemented to predict the response of the joint up to the first failure load and rates up to 10 m/s.

The initial slope, $K_1$, arises due to the compliance of the parent joint material in shear, namely in the X-Z plane. The clamping pressure applied by the bolt on the laminate causes the load to be reacted by friction [1, 5]. Assuming this effect is localized to the clamping region of the bolt (approximately the area under the bolt head or washer [5]) the stiffness $K_1$ can be calculated by Equation 1. This can be shown by means of elastic strain energy considerations, where $A_c$ is the contact area shown in Figure 5, $t$ is the thickness of the laminate and $d_0$ and $d_{fl}$ are the

### Table 5. Final Failure Modes for single-bolt tests

<table>
<thead>
<tr>
<th>C</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{fl}$</td>
<td>FF</td>
<td>FP</td>
<td>FP</td>
<td>FP</td>
<td>FP</td>
<td>FP</td>
<td>FP</td>
<td>FP</td>
<td>FP</td>
</tr>
<tr>
<td>$P_{ab}$</td>
<td>FF</td>
<td>FF</td>
<td>FF</td>
<td>FP</td>
<td>FP</td>
<td>FP</td>
<td>FP</td>
<td>FP</td>
<td>FP</td>
</tr>
</tbody>
</table>

### 3. Model Development

There have been various studies carried out on the quasi-static response of composite bolted joints [1-4] and as a result, the key variables and how they pertain to the characteristic loading curve are relatively well understood. In the majority of the dynamic studies reviewed [5-9], it was found that rate effects on the joint, if present, had the most significant effect on the damaged response, i.e. from the first significant failure load onwards. As mentioned in Sections 1 and 2, one of the key variables in predicting the dynamic response of composite bolted joints appears to be the energy absorption during the propagation of damage.
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diameters of the hole and bolt head/washer respectively.

\[ K_1 = \frac{A_c G_{xx}}{t} \]  
(1)

When loaded above the maximum static friction force, \( P_{fric} \), the laminates will slip relative to one another a distance \( c \) which is approximately equal to the clearance between the bolt shank and the hole. After this the load will then be reacted by the bolt and composite material. This response gives rise to the joint stiffness, \( K_2 \), which is determined from the system of equivalent springs shown in Figure 6. Only the bearing loading case was considered in this study, therefore all springs shown in Figure 6 only have stiffness in the direction of loading. The spring stiffness \( K_{ie} \) and \( K_{2e} \) can again be determined from strain energy considerations and are given by Equation 2 where \( i \) denotes the relevant properties of the \( i \)-th laminate.

\[ K_{ie} = \frac{E_{xx}w_i t_i}{L_i} \]  
(2)

The stiffness term, \( K_B \), accounts for the elastic stiffness of the joint in the vicinity of the bolt. This can be calculated from Equation 3, which was determined by Nelson et al. [13] for single lap composite joints based on Tate and Rosenfeld’s [12] original equation for double-lap isotropic bolted joints. Equation 3 provides a realistic approximation for the joint stiffness as it includes terms to account for the compliance of the bolt in bending, shear and bearing, the composite laminates in bearing, and the effect of the fastener head type on reacting the moment induced by secondary bending (that is present in all single lap joints) by means of the \( \beta \) term. This approach allows the elastic response of the joint to be determined, up until the failure initiation load \( P_{fric} \).

\[ \frac{1}{K_B} = \frac{2(t_1 + t_2)}{3G_b A_b} + \left[ \frac{2(t_1 + t_2)}{t_1 t_2 E_b} + \frac{1}{t_1 \left( \sqrt{E_{xx}E_{yy}} \right)} \right] \left[ 1 + 3\beta \right] \]  
(3)

3.2 Damaged Joint Response Model

There have been a number of attempts in literature to develop an efficient method for determining the damaged response of composite bolted joints [10, 14]. Gray et al. [10] based their approach on the findings of McCarthy et al. [15] by approximating the non-linear damage propagation of joints at quasi-static rates by means of a cubic curve. This method,
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Although very effective for quasi-static load cases, assumed that catastrophic failure of the joint would occur immediately after reaching the ultimate load. This is an invalid assumption for dynamic rates as it can be seen from Tables 3 and 4 that the post-ultimate load response accounts for a significant portion of the energy absorption of the joint. Furthermore, the approach taken by [10] and [15] does not inherently depend on the energy absorbed during loading to calculate the cubic curve. Rather, a control case is required where the loads and tangent stiffness at evenly spaced displacement intervals are taken in order to fit a cubic spline through the experimental data.

Pearce et al. [14] used point link (PLINK) elements from the commercial PAM-CRASH software to account for the damage propagation in dynamic tests. After the initiation of damage, the joint is assumed to experience a period of constant load-extension followed by a linear softening region [16]. These regions are defined by inputting the experienced displacements for the constant load-extension and linear softening regions as well as the energy absorbed during this period of loading. Although this approach does consider the energy absorption of the joint, it simplifies the damage curve, omitting the non-linear damage propagation up to the ultimate load. Additionally, joint displacements are required in defining the damage response, the prediction of which is quite difficult.

As discussed in Section 2, it is clear that the principal variable that affects the response of the joint during failure is the energy absorbed. By basing a method on this parameter as well as the ultimate load carried, any rate effects present are effectively accounted for. This is evident by reviewing Tables 3 and 4. As mentioned in Section 2, it appears that the damage response of the joint consists of a piecewise continuous curve whose shape is dependent on the level of damage in the joint. The initial region is approximately cubic in shape [10, 15] up to the ultimate load and linear to final failure [14, 16]. The forms of the functions used are shown in Equation 4 and illustrated in Figure 7, where $X_{P_{ff}}$ and $X_{P_{ult}}$ are the displacements corresponding to the first significant failure load and ultimate load respectively.

$$f(x) = \begin{cases} a_{11}x^3 + a_{12}x^2 + a_{13}x + a_{14} & \text{if } X_{P_{ff}} < x \leq X_{P_{ult}} \\ a_{21}x + a_{22} & \text{if } x > X_{P_{ult}} \end{cases}$$

(4)

In order to determine the constants from Equation 4 a number of boundary conditions are required. These were based on parameters that were found to be rate dependent and key to the overall damage response of the joint; namely the energy absorption, $P_{ff}$, and $P_{ult}$. The boundary conditions used for determining the cubic region are given in equations 5-9.

$$f(X_{P_{ult}}) = P_{ult}$$

(5)

$$f(X_{P_{ff}}) = P_{ff}$$

(6)

$$\frac{df(x)}{dx} \bigg|_{x=X_{P_{ult}}} = 0$$

(7)

$$\frac{d^2f(x)}{dx^2} \bigg|_{x=X_{P_{ff}}} = 0$$

(8)

$$\int_{X_{P_{ff}}}^{X_{P_{ult}}} f(x) = E_1$$

(9)

Although, it appears that this method requires knowledge of $X_{P_{ff}}$ and $X_{P_{ult}}$ similar to Pearce et al.
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[14], this is not the case. The value of \( X_{Pff} \) can be approximated from the elastic model outlined in Section 3.1. Boundary conditions from equations 7 and 9 require knowledge of the value of \( X_{Pult} \) which is unknown. However, this problem can be overcome by iterating through approximate values of \( X_{Pult} \) until Equation 5 and 9 are simultaneously satisfied. The constants for the linear function can be determined by satisfying Equations 10 and 11.

\[
f(X_{Pult}) = P_{ult} \tag{10}
\]

\[
\int_{X_{Pult}}^{a_{22}} f(x) = E_2 \tag{11}
\]

4. Results
The results obtained from experiments carried out by Egan et al. [9] are compared with those obtained from the model that was developed and outlined in Section 3. These are shown in Figures 8-13. The dynamic tests for joints manufactured from the E-laminate were found to lie on the cusp of two failure modes; fastener failure and fastener pull through. As can be seen in Tables 3 and 4, failure mode significantly affects the energy \( E_2 \). The joints where fastener failure was the dominant final failure mode absorb significantly less energy than those which failed via fastener pull-through. For dynamic cases where two failure modes were present the model was run twice, using the \( E_2 \) value associated with each final failure mode. The solid black line indicates model simulation using the \( E_2 \) value for the dominant failure mode. For the E laminate 5 m/s case the dominant failure mode was fastener pull through whereas the dominant failure mode for the E-laminate 10 m/s case was fastener failure.
5. Discussion

It can be seen in Figures 8 to 13 that an excellent correlation is observed between the model and the experimental test cases, particularly when comparing the response up to the first failure load. This justifies the assumption that for the test velocities considered the joint response is rate independent during the elastic loading regime. Additionally for all test cases, the non-linear damage function which is governed by the energy $E_1$ correlates well with experiments, and a very good estimation of joint displacement at the ultimate load is obtained.

One limitation observed with the model was the linear damage assumption, governed by energy $E_2$. For all joints comprising of the C-layup, and half of the dynamic tests and all quasi-static tests of the E-layup, the linear damage approximation provides a very accurate representation of the joint response to final failure. When these experimental cases were reviewed it was seen that the final failure mode was exclusively either fastener failure or fastener pull-through i.e. there was no mixed-mode failure mechanism in these individual experiments. However, repeats 1 and 3 of the 5 m/s test and repeat 2 of the 10 m/s test of the E-layup joints did not correlate as well with the model during the linear damage region. From Table 5, it can be seen that all of these specimens experienced fastener pull through as the final failure mode. When the specimens were inspected post-testing it was observed that the fastener heads exhibited partial failure [9].

Reviewing the load-displacement curves for these cases in Figures 12 and 13, it can be seen that the initial unloading region is very similar to the cases which failed exclusively via fastener pull-through. The unloading curve then becomes more gradual similar to that experienced by cases which failed via extensive bearing damage followed by fastener pull-through.

This mixed-mode final failure mechanism was exclusive to the thicker E-laminate. Egan et al. [9] attributed this to greater bending moment reacted by the fastener head due the greater ultimate loads carried and the thicker layup. In Section 3.2, when the damage model was developed, a single linear unloading region which implied a single final failure mode was assumed. For the test cases which failed
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exclusively via fastener failure or pull-through modes, an excellent correlation with the model was obtained. This somewhat justifies the use of a linear unloading approximation based on the energy absorption associated with the final failure mode. In order to capture this mixed mode failure it is required to know the loads that a partially-failed fastener can carry. From Figures 12 and 13 this appears to be between 6 and 8 kN, but this is only a set of three cases where the mixed-mode failure was not exclusively the final failure mode; so no definite conclusions can be drawn from this data. Assuming the residual strength of the partially failed fastener is known, along with the energy absorptions corresponding to the individual failure modes, a better correlation could be obtained through the use a piecewise linear function consisting of two segments governed by the energy absorption of each individual mode. However, the mixed-mode failure is not exclusive to any particular loading velocity and it would have to be assumed that both fastener failure and partial fastener failure/fastener pull-through modes are equally likely to occur for dynamic E-layup test cases.

6. Conclusions
Based on the results obtained from the experimental results and the analytical model that was developed, the following conclusion can be made regarding the dynamic response of composite bolted joints:

- For loading rates up to 10 m/s, there appears to be little to no rate effects on the elastic response of the joint.
- For the materials and joint configurations considered, the energy absorption of the joint increase when loading rate is increased from quasi-static to over 5m/s.
- The energy absorption of the joint is dependent on the final failure mode. Using this energy, a reasonable prediction of the joint response during failure can be obtained.

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