IMPACT ON BONDED REPAIRS TO CFRP LAMINATES UNDER LOAD

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Abstract

A preliminary experimental study was conducted to assess the impact tolerance of carbon epoxy composite panels incorporating a 5^o scarf joint with no surface overplies under various levels of tensile preload, to a 14.5 J impact. This was compared to the impact tolerance of plain panels. The panels were prestrained in the range of 0 to 3000 με, the maximum value corresponding to a typical design limit load. For the plain panel specimens, the level of preload was found to have largely no effect on the impact damage area for the range of loads examined, which was low in relation to their ultimate tensile strength. However, the behaviour of the scarf joint specimens was found to be sensitive to the level of the prestrain. From the limited experimental data, the impact tolerance of the scarf joint specimens with no surface overplies appeared to be lower than the plain panel specimens, with catastrophic failure occurring in one instance at the very high prestrain of 3000 με.

1 Introduction

Bonded composite patches are often used as an economical repair strategy to restore the strength of heavily loaded aerospace structures after impact damage or fatigue cracking. This may be in the form of scarf repairs in the case where there is a requirement for a flush surface, or external patch repairs when the surface condition is not critical. Scarf repairs are commonly implemented with additional external overplies to improve damage tolerance, unless extreme surface flushness is required (e.g. for stealth or aerodynamic considerations). Significant cost savings may be realised compared to the alternative of component replacement [1].

Bonded repairs on the external surface of an aircraft are subject to the same impact risks as those of the parent structure. Consequently, an understanding of the impact response and tolerance of such repairs is essential to enable the assessment of their effectiveness and durability.

The impact resistance of polymer composite laminates has been a topic over intensive investigation of many years, which has been reviewed by Abrate [2] and Ried et al. [3]. Most of the impact studies on composite structures reported in the literature have been conducted with the impact taking place on unloaded structures. This however, does not truly represent events likely to be encountered in real life, such as runway debris impact and bird strikes. In the limited literature on the impact of preloaded composite structures, it has been reported that catastrophic failure was found to occur in cases when the panels were impacted at levels which when applied to the unloaded panels did not reduce significantly their residual strength [4].

This paper examines the behaviour of composite bonded scarf patch systems to impact whilst under tensile loading. A 5^{o} scarf joint with no surface overplies in a 3.2 mm thick, quasi-isotropic carbon epoxy panel is considered. This is representative of the extremely flush structural repair and is therefore conservative. The severity of the impact damage generated under different levels of preload was determined experimentally under an nominal impact energy of 14.5 J (approximately 1000 lb in/in). The implications for the design of these repairs are discussed in this context.

2 The Scarf Joint

A typical scarf joint is shown in Figure 1. The scarf joint is engineered such that it restores the full design ultimate strength of the parent structure [5]. In order to achieve this, a very shallow scarf angle is normally used so that the adhesive shear stress is kept low.

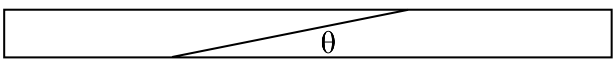


Fig. 1. Cross-section of a scarf joint

The allowable scarf angle may be calculated using the following expression [5]:

$$\theta \leq \frac{\tau_{adh}}{\varepsilon_u E} \qquad (1)$$

where θ is the scarf angle in radians, τ_{adh} is the adhesive shear strength, ε_u and E are the design ultimate strain and modulus of the parent structure. Note that this formulation is based on a 2D full-width scarf joint where load bypass is not available, and is hence conservative.

Using a high-performance film adhesive with a hot-wet (105^{o}C, 100% relative humidity) strength of 20 MPa, bonded to a carbon/epoxy parent structure with a design ultimate strain of 4000 με and modulus of 70 GPa, the maximum scarf angle can be calculated to be 4^{o}. However, a larger scarf angle may be used due to load bypass around the repaired region, and particularly if the stringent hot-wet condition is not required. It is desirable to use the largest possible scarf angle in order to minimise the amount of material which needs to be removed from the parent structure.

Based on finite element analyses, Soutis and Hu [6] have reported that the angle for the composite scarf repair which they examined, could be increased from 4^{o} to almost 7^{o} when the effect of bypass was included in the model.

In this study, a 5^{o} scarf angle was used and all mechanical tests were conducted under laboratory controlled room temperature-dry conditions. Furthermore, it was considered unlikely that impact of repairs would occur under the hot-wet condition with no structural load bypass available.

3 Experimental Study

Impact tests were conducted on plain composite panels and panels incorporating a 5^{o} full-width scarf joint in their middle. The tests were conducted at various specimen preloads to produce prestrains ranging from 0 to 3000 με (nominal). The specimens, supported only in the grips of the test-rig, were impacted at their centre point with a nominal impact energy of 14.5 J. The impact damage area was then determined by C-scan. A schematic of the scarf joint test specimen is shown in Figure 2. The test matrix is presented in Table 1.

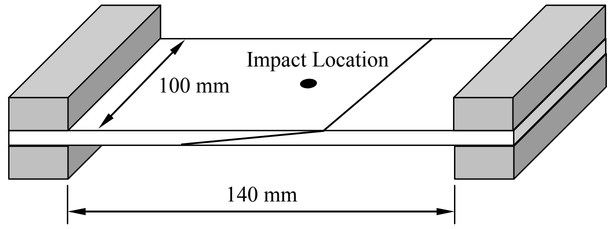


Fig. 2. Schematic of scarf joint specimen installed in friction grips

Table 1. Test matrix and summary of impact test results

Specimen Type	Prestrain (με) (± 50)	Impact Velocity (m/s) (± 0.1)	Damage Area (mm^2) (± 25)	Specific Damage Area* (mm^2/J) (± 2)
Plain	0	10.3	310	19.2
Plain	1130	9.2	210	16.5
Plain	2070	10.7	360	20.6
Plain	3110	9.8	200	13.4
Plain	3200	9.0	230	18.8
Scarf	0	10.7	520	29.5
Scarf	1090	10.0	240	15.5
Scarf	1980	10.3	460	28.4
Scarf	2960	9.5	90	6.3
Scarf	3060	8.3	Failed	

*Damage Area / Impact Energy

3.1 Specimen Design and Manufacture

A quasi-isotropic carbon/epoxy panel was used as the subject of this study. The material used was the Cycom T300/970 prepreg system with a ply thickness of 0.2 mm. The 16 ply lay-up sequence was $[45\ 0\ \text{-}45\ 90]_{2s}$ which yielded a nominal panel thickness of 3.2 mm. This was considered representative of typical composite aerospace structures.

The dimensions of the test panels were 100 mm wide by 200 mm long. The width was chosen so that the impact damage would not occupy the entire span of the specimen. This would also allow compression-after-impact (CAI) tests to be conducted on 100 mm x 150 mm specimens cut from the panel, in a standard CAI test rig, as part of the planned continuation of the work presented in this paper.

In order to compare the performance of the scarf joint against that of the parent structure, both plain panels and scarf joint specimens were prepared. The scarf joint specimens were machined in a computer numerically controlled mill, fitted with a ½ in. ball nosed diamond coated tool, to produce a 5^o scarf which was bonded using FM73 structural film adhesive with a nominal thickness of 0.38 mm. No additional surface preparation was made to the freshly milled scarf surfaces other than light dusting with an air jet. The total length of the bondline was approximately 37 mm. The adhesive was cured at 120^oC for 2 hours under a 1 atmosphere vacuum.

It must be emphasised that the specimen design was conservative and represented the worst case scenario from the perspective of strength restoration as no overplies were incorporated. In real repairs, overplies are almost always used except in the rarest circumstances to protect the scarf tip and to improve the damage tolerance of the repair [5].

3.2 Impact under Preload Testing

The experimental work was conducted using the test rig at Monash University, designed for impact testing on biaxially loaded panels. This system is described in more detail by Whittingham et al [7]. A tensile preload was applied to the test specimens along the length direction using a hydraulic ram of 100 kN capacity, via friction grips, each extending over 30 mm of the specimen length. The specimens were only supported at the grips leaving an unsupported region of 100 mm by 140 mm. A photograph of the test set-up is shown in Figure 3.

The applied prestrain was calibrated using strain gauges attached to the surface of two calibration specimens, one plain specimen and one scarf specimen. The gauges were located at the centre of the specimen which was the point of impact. In subsequent tests, the specimen applied strain was determined from the ram pressure readings using the calibration curves for the respective specimen types. The load corresponding to the same strain was about 5% higher for the plain panel specimen compared to the scarf specimen due to the reduced stiffness in the scarf region. This system was able to apply a maximum strain of just over 3000 με before the onset of significant grip slippage. Therefore, the maximum prestrain applied to the test specimens was limited to 3000 με (nominal). The grips are presently being redesigned so that higher preloads may be applied to the specimens for future tests.

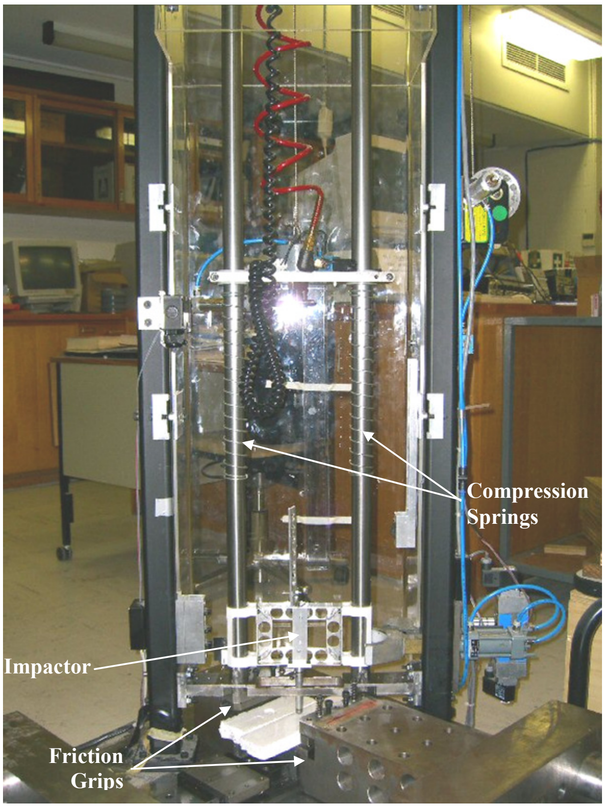


Fig. 3. Impact under load test set-up showing the compression springs over the impactor guide rails

In order to maximize the impact velocity, two compression springs were installed over the impactor guide rails, as may be seen in Figure 2, to provide additional stored energy. The impact velocity was measured by a photo interrupter system, activated by a tab extending from the impactor. The impactor assembly, including its guides had a mass of 305 g. A nominal impact energy of 14.5 J was chosen which corresponds to approximately 1000 lb in / in, with a corresponding impact velocity of 9.75 m/s. The compression springs, combined with a drop height of approximately 3 m, produced an impact velocity between 8 m/s and 11 m/s. The corresponding impact energy was between 10 J and 17 J.

The specimens were impacted at their centre, which was approximately 20 mm from the scarf tip in the case of the scarf joint specimens. A 12 mm diameter hemispherical steel impactor head was used. This was considered representative of low-velocity runway debris impact.

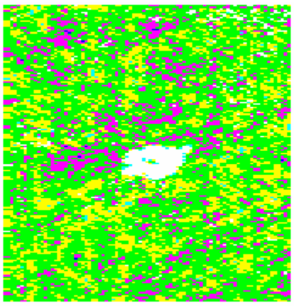
To investigate the effect of the preload, the specimens were impacted at different strain levels whilst keeping the impact velocity approximately constant. The preloads examined were those producing nominal prestrains of 0, 1000 με, 2000 με and 3000 με. The maximum strain applied corresponded to the limit load condition for typical composite aerospace structures [5]. A total of 10 specimens, five each for the plain panel specimens and the scarf joint specimens, were tested. Two specimens of each type were impacted with a nominal prestrain of 3000 με.

4 Results and Discussion

All of the specimens tested showed a small indentation at the impact site. Damage in the form of fibre splitting and matrix cracking on the underside (45^{o} ply) could also be seen on most specimens. This was generally less severe on the impacted plain specimens compared to the impacted scarfed specimens. Curiously, one of the scarf joint specimens impacted at 3000 με showed no visible damage on the underside whilst the other failed catastrophically.

The test specimens were subsequently C-scanned and the areas of the internal damage were measured. The C-scan images for the plain panel specimens are shown in Figure 4, and those for the scarf joints are shown in Figure 5. The scarf region can be clearly seen in Figure 5. A summary of the results is presented in Table 1.

The impact velocity and hence the impact energy varied from test to test. In order to compare results for the projected damage area, a specific damage area was defined, being the projected damage area divided by the impact energy. This relies on the fact that the damage area will vary linearly with impact energy for small changes in impact energy. Figure 6 shows the specific damage area plotted against the prestrain.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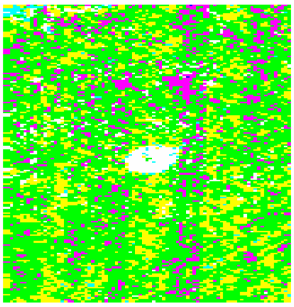
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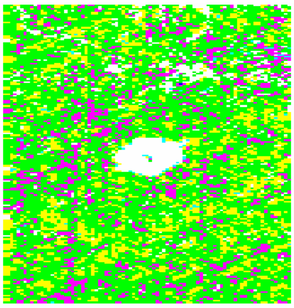
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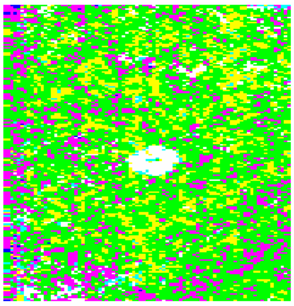
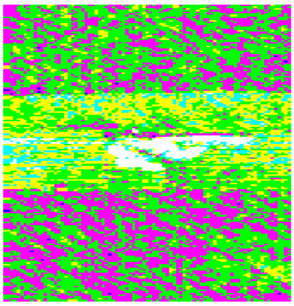

(d)

Fig. 4. C-Scan images of impacted plain panel specimens at: (a) 0 prestrain, (b) 1000 με prestrain, (c) 2000 με prestrain, and (d) 3000 με prestrain. Load applied in vertical direction.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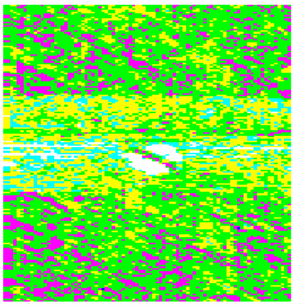
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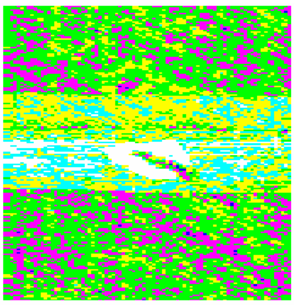
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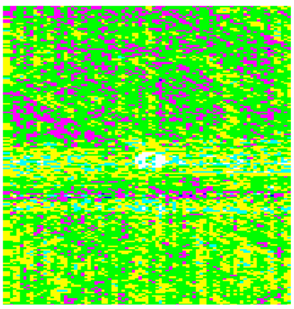
(d)

Fig. 5. C-Scan images of impacted scarf joint specimens at: (a) 0 prestrain, (b) 1000 με prestrain, (c) 2000 με prestrain, and (d) 3000 με prestrain. Load applied in vertical direction.

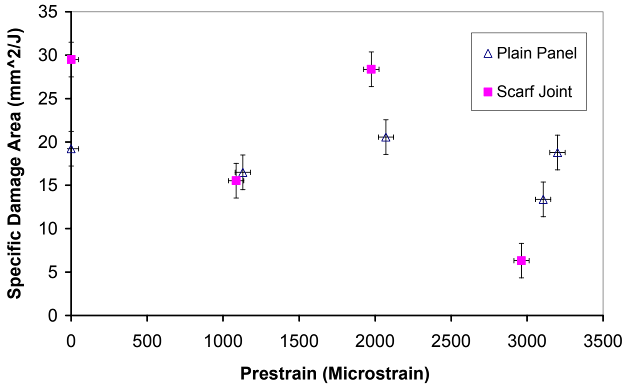

Fig. 6. Specific damage area with varying prestrain for both the plain panels and scarf joint specimens

Herszberg et al [4] have reported that similar tests on plain specimens lead to catastrophic failure when preloads and impact velocities were above a critical value. It can be seen from Figure 6 that the specific damage areas for the plain panel specimens in the present study were largely independent of the preload for the range of strains examined and catastrophic failure did not occur. This is believed to be due to the low strain levels achieved in the test (the maximum strain was approximately 25% of the ultimate tensile strain). Evidently, the testing regime in the present study was remote from the load and impact velocity required to cause catastrophic failure.

The scarf joint specimens exhibited an interesting behaviour. The specimen with zero prestrain exhibited significant visible damage on the side remote from the impact. The C-scan image also revealed large internal damage, presumably in the form of delamination and fibre breakage (see Figure 5a). The specific damage area (and therefore the impact susceptibility) was significantly greater than the plain panel specimen under zero load, as may be seen from Figure 6. This is believed to be due to large bending of the specimen during the impact which gave rise to high stresses in the scarf joint. The level of bending would be slightly greater for the scarf joint specimens compared to the plain panel specimens due to the fibre discontinuity across the bonded region and the corresponding reduction in flexural stiffness. The bending-induced adhesive stresses would be significantly higher than the matrix stresses in the plain panel due to the lack of fibre reinforcement. Most applications of scarf repairs incorporate surface overplies. It is believed that if overplies were applied to the scarf joint specimens, the damage region may be reduced. Such overplies have been shown to reduce the adhesive peel stresses in scarf joints, particularly at their tip [8], and in this case, would also provide increased flexural stiffness.

It is interesting to note that for unloaded low velocity plain panel impact specimens, it has been shown by various researchers that the level of damage bears an inverse relationship to the amount of bending during impact, because energy is expended to elastically deform the structure [9,10]. However, it appears that the same cannot be said for scarf joint specimens as shown in this study. The high adhesive stresses produced as a result of bending during impact appeared to have negated any favourable effect of elastic energy absorption.

When the scarf joint specimen was subjected to a 1000 με nominal prestrain, the damage area was significantly reduced (see Figure 5b). The increased flexural rigidity as a result of the tensile prestrain reduced the level of bending of the specimen during impact. The level of the preload was much less than the ultimate tensile strength of the adhesive joint. Therefore, the overall result was beneficial. At this point, the impact resistance of the scarf joint can be seen to be similar to that of the plain panel specimen.

However, when the prestrain was increased to about 2000 με, the specific damage area of the scarf joint again increased, to a level comparable to that for the unloaded specimen and well above the corresponding value for the plain specimen. In this case, the shape of the internal damage was different, as may be seen in Figure 5c. Further testing may show this result to be an outlier.

The behaviour of the scarf joint specimen at a prestrain of around 3000 με was most irregular. One specimen showed very little impact damage (see Figure 5d) whilst another failed catastrophically during impact. The latter was subjected to a slightly higher prestrain although the impact velocity was lower (see Table 1). The failure is presumed to have been caused by adhesive failure around the tip of the scarf joint remote from the impact, as shown in Figure 7. This would be a point of maximum combined stresses under bending induced by the impact. Once initiated, the disbond can be seen to have traversed into the composite substrate itself.

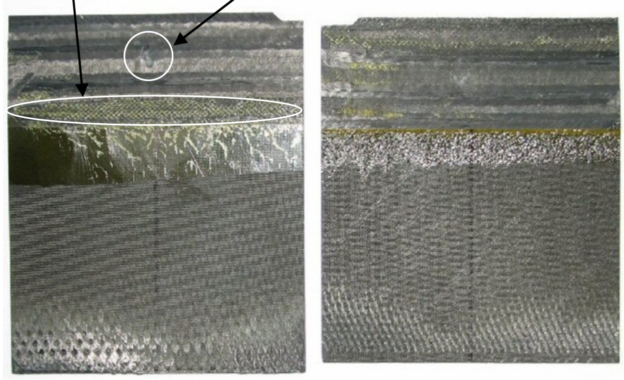

Fig. 7. Failed scarf joint specimen (3000 με prestrain) showing adhesive failure around the tip of the scarf joint on the underside (left) and subsequent adherand failure. A small direct impact damage at the impactor site can also be seen (circled).

In addition to the bondline damage, a small direct impact damage can also be seen, as shown in Figure 7. The size of this damage is almost identical to that of the other specimen impacted at the same level of prestrain as indicated by the C-scan.

It is not known at this stage whether the catastrophic failure was a result of a weak bond, or the impact event itself. Further experimental testing is required to ascertain the behaviour of the scarf joint at this combination of preload and impact energy. It is importance to determine unequivocally the behaviour of the repair at 3000 με, because this level of loading corresponds to the design limit load for typical composite aerospace structures. In addition, all specimens need to be tested for residual strength in order to assess the effect of the impact damage on the structural integrity.

5 Design Implications

The design of scarf repairs has hitherto been based solely on static strength requirements [5]. Consequently, the impact tolerance of such repairs has been largely neglected. However, It can be seen from the limited preliminary test results that the impact tolerance of the scarf joint with no surface overplies, in terms of the damage area, appears to be lower than the parent structure in most cases, except when lightly loaded (1000 με prestrain). Therefore, the repaired structure cannot be expected to retain the same level of impact performance as the undamaged parent. (This is also true in the sense of static strength by virtue of the design philosophy.) Of note is the indication that catastrophic failure may occur as a result of impact at panel strain levels of 3000 με which is at the extreme of the normal design limit load values. However, the probability of an impact event occurring at this high a strain level is extremely remote.

The test results were obtained for simple scarf joint with no surface overply. It is believed that the addition of an overply may improve the impact resistance by increasing the flexural stiffness of the repaired region and thereby reducing the adhesive stresses during impact. Naturally, further testing is required to confirm this hypothesis. If proven, this would reinforce the importance of the overply in the implementation of the scarf joint as previous shown by Gunnion et al. from the perspective of static strength [8].

It must be noted however, that the test results are relevant only to monolithic composite structures with limited support against bending. The behaviour of fully supported sandwich structures may be significantly different due to the different support conditions. This is particularly important for the catastrophic failure case.

6 Conclusion

An preliminary experimental study based on a limited number of specimens has been conducted to assess the impact tolerance of scarf repairs to carbon/epoxy composite structures under load. Both quasi-isotropic plain panel and 5^o scarf joint specimens without surface overplies were examined so that a comparison could be made between the repair and the undamaged parent structure. The specimens were manufacture using Cycom T300/970 prepreg system with a nominal thickness of 3.2 mm. FM73 structural film adhesive was used to bond the scarf joint specimens. The specimens were impacted by a 12 mm hemispherical steel impactor at a nominal impact energy of 14.5 J, under 0, 1000, 2000 and 3000 με of nominal prestrain. The highest strain level achieved corresponds to typical design limit load condition for composite aerospace structures.

It was found that the specific damage area (damage area / impact energy) of the plain panel specimens was largely independent of the level of prestrain for the range of strains applied, which was low in relation to the ultimate tensile strain (~25%).

The non-overplied scarf joint specimens were found to have a lower damage tolerance (greater specific damage area) compared to the plain panel specimens in general. This is believed to be due to the lack of support against bending during impact, which produced high adhesive stresses. It is speculated that the incorporation of a surface overply, which is normally applied in real repairs, may offer appreciable improvement, although further testing is required to confirm this hypothesis.

One scarf specimen failed catastrophically when impacted while under a high prestrain of around 3000 με, while a second specimen suffered only minor damage in this condition. The behaviour of the scarf joint impacted under a 3000 με prestrain could not be categorically determined in this study due to the inconsistency in the limited test results. Further testing is planned to re-examine this subject and to determine the effect of the impact damage on the residual strength of the specimens.

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