1 Introduction
Advanced structural adhesives are widely used in joining primary and/or secondary structural members and manufacturing of advanced composite materials. In addition, it is commonly applied in the repair of the structures. Advantages of adhesive bonding over traditional joining techniques such as welding and riveting include ease in assembly process, elimination of material removal and hence more uniform load distribution and thus reduced stress concentration, better fatigue resistance, higher corrosion resistance, substantial weight reduction, and flexibility in joining different materials [1-2]. These in turn lead to improved production and quality, and reduced production and maintenance cost.

External patch repair is considered as a temporary repair. This method has the advantages of simple and less preparation time compared to other adhesive repair methods such as scarf and step sanded repairs. It can be implemented by removing the damaged region, followed by patches attachment using an adhesive. However, this method requires good surface preparation. Besides, external patches lead to aerodynamics disturbance and load path eccentricity that causes high shear and peel stresses at patch edges [3].

Several studies on the tensile behaviour of external patch repaired carbon/epoxy composite are available in the literature [4-6]. For example, Liu and Wang [4] studied the tensile behaviour of T300/QY8911 carbon fibre reinforced polymer (CFRP) composite-composite repairs bonded by J159 adhesive. In their studies, the stacking sequence of the parent plate was always [(0/90/±45/90/0)_{2s}] and the adhesive thickness was fixed at 0.12mm. Through experimental observation, the authors reported that depending on the size and the stacking sequence of patches, the failure of the repaired composites could be caused by patch’s debonding or fracture. However, due to the variation in both patch diameter and patch stacking sequence at the same time, it is difficult to conclude the effect of each parameter separately in their studies.

Campilho and his co-workers [5] characterised the tensile behaviour of single- and double-sided patch repaired composites. Both parent plate and patch were fabricated from Texipreg HS 160 RM CFRP composite prepreg. Their study was limited to cross-ply laminates for both parent plate and patches. The lay-up of the parent plate was [0_s/0_s], and the parent plate and the patch were bonded by Araldite2015 adhesive at 0.2mm thickness. Their results showed that double-sided patch repairs exhibited slightly higher failure load compared to single-sided patch joints at all overlap lengths and patch thicknesses. Specifically, improvement in the failure load was observed in double-sided repairs at all patch thicknesses with overlap length of 10mm compared to the notched specimens, but not in single-sided repairs. For both single- and double-sided repairs, low overlap length led to premature patch debonding and the failure load was even lower than the notched specimens.

Cheng et al. [6] investigated the patch bonded composite repairs made by T600S/R368-1 CFRP prepreg under tensile loading. The stacking sequence of the parent plate was [45/-45/0/90]_{2s}. The repair
systems were prepared by bonding the patches to the parent plate using ESP110 adhesive at 0.2mm thickness. It was reported that patch membrane stiffness, $A_{11}$ of 11.4GPa (where the patch stacking sequence was $[\pm 45]_S$) gave the best load recovery. Besides, if the membrane stiffness was the same, the stacking sequence had negligible affect on the failure load of the repairs. However, significant edge delamination was observed in the parent plate due to $90^\circ$ layers as mid-plies.

Based on the literature survey discussed above, several design parameters in the repair system are chosen in the present work. Firstly, the stacking sequence of the parent plate is selected as $[45/90/-45/0]_S$ with the intention to minimise the edge delamination. In addition, the quasi-isotropic laminate is repaired using shear dominated patches ($[\pm 45]_S$ and $[\mp 45]_S$) of the same type of composite. Besides, in order to observe the effects of adhesive type on the repair systems, patches are bonded using two different types of epoxy based adhesives: Araldite2015 and ESP110. Furthermore, effects of sandpaper polished and plasma treated repairs are investigated as well. Moreover, the experimental testing of composite repairs is accompanied by acoustic emission analyses.

2 Materials and methods
2.1 Fabrication of composite plates
The material used for both parent plate and patch is T600S/R368-1 carbon/epoxy prepreg supplied by Structil. Composite laminates are fabricated using hand lay-up technique with curing cycle shown in Figure 1. The stacking sequence of quasi-isotropic parent plate is $[45/90/-45/0]_S$, and composite plate of $[0/90]_S$ is fabricated for patches.

2.2 Preparation of testing coupons
The cured parent plate is cut into specimens of 250×50mm² size using diamond coated abrasive cutting blade with coolant. For notched and repaired specimens, a central hole of 10mm diameter was drilled, which gives the diameter to width ratio as 0.2. Circular patches of 35mm diameter are prepared through milling. This provides a constant overlap length of 12.5mm.

In this study, two types of epoxy based adhesives are used, one of them is a two-part ductile adhesive Araldite2015 and another one is a single-part brittle adhesive ESP110. The major mechanical properties of both adhesives are listed in Table 1. It should be noted that ESP110 adhesive is not perfectly brittle. Nevertheless, it is comparatively stiffer and more brittle than Araldite2015. For the patches, two stacking sequences are employed, which are $[\pm 45]_S$ and $[\mp 45]_S$, to provide the same membrane stiffness of the patch. Besides, two surface preparation methods: sandpaper polishing and plasma treatment, are employed to investigate their effects. For sandpaper polished specimens, surfaces are first polished with fine grade sandpaper and followed by cleaning with acetone before bonding. As for plasma treated samples, the bonding surfaces are cleaned by iso-propanol before the treatment using plasmatreat PT60 at 3m/min. Patches are bonded to the parent plate immediately after the surface treatment. To ensure uniform and consistent adhesive thickness of 0.2mm across the bonding surfaces, the adhesive bonded composites are clamped with steel plates with controlled thickness bars on both sides of the plates. Composite plates bonded with Araldite2015 are heated at 50°C for 2 hours, whereas for ESP110 bonded specimens, 120°C for 1 hour is applied for adhesive curing.

All specimens are then bonded with glass/epoxy tabs of 50mm length on both ends of the specimens. The configurations of unnotched, notched and repaired specimens are shown in Figure 2, and Table 2 summarises all the tests conducted for repaired specimens.

2.3 Testing and data acquisition
Quasi-static tensile test is carried out using a universal testing machine with load cell capacity of 100kN at crosshead speed of 1mm/min. At least three replicates are tested for each type of specimen. In addition, acoustic emission equipment is used for repaired specimens, with the threshold value set to be 45dB. In order to identify the location of damage events in the repairs, three transducers are attached to the specimen, located at the centre (on the patch) and 40mm on both sides from the centre on the parent plate (Figure 3).
3 Results and discussion

3.1 Comparison among remote tensile strength

Figure 4 compares the remote tensile strength of unnotched, notched and repaired specimens with two different adhesives, patch stacking sequences and surface treatment methods, where the name of each type of the repaired specimen is explained in Table 2. The values of remote tensile strength are calculated based on the nominal area of the specimen (width x thickness). Values in bracket are the coefficient of variation, whereas values in red refer to the residual strength as compared to the unnotched specimens. Results reveal that a reduction in the area of 20% (notched specimens) leads to 51% reduction in the strength because of local stress concentration at the transverse edges of the hole. Consider that the effect of local stress concentration (ELSC) on the remote tensile strength can be represented by Equation (1) as following:

\[ ELSC = \frac{\sigma_{un}}{\sigma_n} \left(1 - \frac{d}{b}\right) \]  

(1)

where \( \sigma_{un} \), \( \sigma_n \), are the remote strength of unnotched and notched specimens, and \( b \), \( d \) and \( t \) corresponds to the width, hole diameter and thickness of the parent plate. In this case, the ELSC is calculated as 1.62. In addition, it is shown that at least 72% of strength is recovered with external patches repair, which is comparable to the strength recovery reported in the literature [4,6]. Repaired with ESP110 adhesive exhibits better performance compared to Araldite2015 (13% and 7% for the systems repaired by patches [±45]s and [∓45]s, respectively). It means that the behaviour of the adhesive used could influence the performance of the repaired systems. Based on the mechanical properties displayed in Table 1, it is postulated that the remote tensile strength of the repairs is more influenced by the strength of the adhesive rather than the failure strain. Besides, regardless the type of adhesive used, variation with the patch stacking sequence is not significant, with maximum of 3% difference. Previous study has also reported that effect of patch membrane stiffness dominates over the patch lay-up sequence if the damage in the adhesive/adherend interface is not the major failure mode [6]. Moreover, negligible effect is found between different surface treatments. This observation allows concluding that the behaviour of adhesive/adherend interface does not play an essential role in the failure of the repairs in this study.

3.2 Fracture mode of the specimens

Figure 5 shows the fracture surfaces of unnotched and notched specimens. It can be seen that both unnotched and notched specimens fail in 90° and -45° directions. In addition, edge delamination is not observed in both specimens. This fulfils one of the objectives of this study. In the previous study from the laboratory with 90° as mid-plies, significant edge delamination was observed [6]. The fracture surfaces of tested repairs are presented in Figure 6. It can be seen that the fracture mode of the repaired composites is mainly influenced by the material behaviour of the adhesive, but not by the patch stacking sequence and surface treatment method. For ductile adhesive (Araldite2015) repaired systems, partial patch debonding is always observed in sandpaper polished specimens, whereas one-side total patch debonding could be observed occasionally in plasma treated specimens. Two-side total patch debonding is noticed in brittle adhesive bonded joints (ESP110) in all cases. This could be caused by unstable crack propagation at peak load due to dynamical effects, as generally happened in most of the brittle materials. Besides, it is noteworthy that all these fracture modes are similar to Mode A failure mentioned in reference [4], where patches are strong enough and debonding occurs due to high shear and peel stresses in the adhesive layer which are generally recognised to be at the region near the edges of the patch. In addition, the fracture pattern of all parent plates is the same, where the fracture path is in 90° and -45° directions.

Figure 7 shows the optical micrographs of the fracture surfaces for the cases with debonded patches. It is obvious that some parent plate material pieces are attached on the patches, and patch debonding is resulted from delamination of the parent laminate and a mixture of interface and cohesive failure. This implies strong adhesive/adherend interface. Patches seem to be still intact or with minimal damage.
3.3 Acoustic emission analyses

For the purpose of following the damage evolution in the repairs, acoustic emission (AE) data is taken at several intervals throughout the tensile test. The distribution of AE amplitudes with respect to the damage mechanisms are categorised using the classification by other researchers [10-12], which are shown in Table 3. Figure 8 presents the AE amplitude versus the event position at different relative elongation levels of ARA-sp repair. Here, the relative elongation refers to the ratio of the instantaneous elongation to the elongation at failure load. The energy level of the events is represented by different colour. It can be seen that damage first occurs in the amplitude range of 45-60dB with energy less than 5J and concentrated at the right region (Figure 8(a)). By referring to Table 3, this is most probably corresponding to matrix cracking. Later on, damage events within the amplitude range of 60-80dB at energy level less than 35J are observed and located around the edge of the notch (Figure 8(b)). This could indicate delamination initiation. In addition, it is expected that adhesive damage could have occurred as well. It seems to be reasonable to say that because both interface delamination and adhesive damage imply damage in the epoxy. Finally, damage events at high energy level within the amplitude range of 80-100dB are observed, as depicted in Figure 8(c). This is believed to be corresponding to fibre breakage.

AE data of ESP-sp at the same relative elongation is shown in Figure 9. Since the only difference between both repairs is the adhesive type, it is believed that the same categorisation predicted for ARA-sp repair can be referred: 45-60dB for matrix cracking, 60-80dB for interface delamination and adhesive damage, and 80-100dB for fibre breakage. Contrary to ARA-sp repair, Figure 9(a) shows that some high energy events (>5J) are noticed at relative elongation of 0.65. The one near the centre location has an amplitude value close to 60dB, which may indicate interface delamination or adhesive damage. Another two damage events with energy level greater than 5J are most probably indicating interface delamination, since they fall outside the repair zone (±17.5mm). These observations suggest that adhesive damage and interface delamination could have occurred earlier in ESP-sp repair. Beyond that, the damage events at relative elongation of 0.82 and 1 in ESP-sp repair are similar to ARA-sp repair.

4 Conclusions

In this present work, experimental studies on unnotched, notched and repaired quasi-isotropic composite laminates are carried out. Specifically, for composite repairs, the effects of adhesive type, patch stacking sequence and surface treatment method are investigated. Based on the results obtained, it can be concluded that:

i. All unnotched, notched and repaired parent plates fail in 90° and -45° directions. Edge delamination is not observed in all parent plates.

ii. The residual strength of the notched specimen is only 49% of the unnotched one, which is believed to be due to local stress concentration effect at the transverse notch region.

iii. Adhesive type has a more significant effect on the remote tensile strength of composite repairs compared to patch stacking sequence and surface treatment method, with a maximum of 13% higher strength in ESP110 adhesive bonded composites.

iv. Partial patch debonding is always observed in Araldite2015 repairs with sandpaper polishing method and one-side total patch debonding is occasionally observed in plasma treated Araldite2015 bonded joints. As for ESP110 repairs, two-side total patch debonding always occurs in all cases.

v. Optical micrographs taken on the debonded patches show that patch debonding is resulted from the delamination of the parent laminate and a mixture of interface and cohesive failure. Patches seem to be still intact or with minimal damage.
vi. Through comparison with the published data, it is suggested that for the composite repairs tested in this study, the corresponding AE amplitudes for the damage mechanisms can be classified as: 45-60dB for matrix cracking, 60-80 for interface delamination and adhesive damage, and 80-100dB for fibre breakage.

Table 1
Major mechanical properties of Araldite2015 and ESP110 adhesives.

<table>
<thead>
<tr>
<th></th>
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<th></th>
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</thead>
<tbody>
<tr>
<td>Young’s modulus, E (MPa)</td>
<td>1850</td>
<td>6000</td>
</tr>
<tr>
<td>Poisson’s ratio, ν</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>Tensile yield strength, σ_y (MPa)</td>
<td>13</td>
<td>40</td>
</tr>
<tr>
<td>Tensile failure strength, σ_f (MPa)</td>
<td>22</td>
<td>64</td>
</tr>
<tr>
<td>Tensile failure strain, ε_f (%)</td>
<td>4.77</td>
<td>2.33</td>
</tr>
</tbody>
</table>

Table 2
Series of repaired specimens tested in this study.

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Surface treatment</th>
<th>Patch stacking sequence</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Araldite 2015</td>
<td>Sandpaper</td>
<td>[±45]_s</td>
<td>ARA+sp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[±45]_s</td>
<td>ARA-sp</td>
</tr>
<tr>
<td></td>
<td>Plasma</td>
<td>[±45]_s</td>
<td>ARA-pl</td>
</tr>
<tr>
<td>ESP110</td>
<td>Sandpaper</td>
<td>[±45]_s</td>
<td>ESP+sp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[±45]_s</td>
<td>ESP-sp</td>
</tr>
<tr>
<td></td>
<td>Plasma</td>
<td>[±45]_s</td>
<td>ESP-pl</td>
</tr>
</tbody>
</table>

Table 3
Classification of AE amplitudes with respect to damage mechanisms.

<table>
<thead>
<tr>
<th>Ref</th>
<th>MC</th>
<th>INT</th>
<th>DLM</th>
<th>PoB</th>
</tr>
</thead>
<tbody>
<tr>
<td>[10]</td>
<td>40-60</td>
<td>50-70</td>
<td>60-80</td>
<td>80-100</td>
</tr>
<tr>
<td>[11]</td>
<td>50</td>
<td>-</td>
<td>62</td>
<td>-</td>
</tr>
<tr>
<td>[12]</td>
<td>40-70</td>
<td>-</td>
<td>-</td>
<td>60-100</td>
</tr>
</tbody>
</table>

* MC-Matrix cracking, INT-Fibre/matrix interface debonding, DLM-Interface delamination, PoB-Fibre pull-out and/or breakage. All values are in dB.
Fig. 4. Remote tensile strength of all series of specimens.

(a) Unnotched
(b) Notched

Fig. 5. Fracture surface of unnotched and notched specimens.

(a) ARA+sp
(b) ARA-sp
(c) ARA-pl
(d) ESP+sp
(e) ESP-sp
(f) ESP-pl

Fig. 6. Fracture surface of all series of composite repairs.
Fig. 7. Optical micrographs of the patches debonded from the repairs.

(a) ESP+sp
(b) ESP-sp
(c) ESP-pl
(d) ARA-pl

Fig. 8. Acoustic emission amplitude and energy versus position of events at various damage occurrence levels of ARA-sp repair.
Fig. 9. Acoustic emission amplitude and energy versus position of events at various damage occurrence levels of ESP-sp repair.

**References**


