Experimental Assessment of Effectiveness of Adhesives for Field Repairs of Army Aviation Ballistic Protection Panels

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This report aims to describe the testing program used for the verification of a new adhesive for use by the Australian Regular Army’s Aviation Corp for field repairs of ballistic protection panels. The testing had to verify that the adhesive could withstand minimal surface treatment, different materials and the effects of humidity (environmental conditions) in order to be deemed satisfactory. Other areas of interest were also researched, such as the effect of cure time and the use of minimal surface treatment with different solvents. From this information a recommendation will be passed through DSTO to Army Aviation on the researched adhesives. A total of one hundred and eleven samples were produced and tested using flatwise tensional testing, these results are detailed and discussed in this report.

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ACCOROMS
ACE............................................................................................................................Armour Composite Engineering
DSTO............................................................................................................................Defence Science and Technology Organisation
MEK...............................................................................................................................Methyl Ethyl Ketone
MST.................................................................................................................................Minimum Surface Treatment

APPENDICES
Appendix A. ADHESIVE DATA ......................................................................................... A1

1 PLTOFF, School of Engineering & Information Technology.
I. Introduction

A. Background

A bonding issue with the helicopter ballistic protection panels was reported to DSTO from DSTO’s Army Aviation client. To best resolve this issue a new adhesive is required. This adhesive needs to be able to bond 6061-T6 Aluminium, silicon carbide tiles and a multi-ply Aramid lay-up in the field environment with sufficient strength [1].

Previous testing [1] revealed that the average strength of these panels under Flatwise tensional testing was 0.87 MPa, with a failure mode of delamination of the Aramid fibre layup. The tested adhesives are to be compared to these results and a factor of safety of 2 is required for the adhesive to be deemed suitable.

ACE P/L provided three adhesive samples (DSTO #1-3 – Appendix A) that are polyurethane based adhesives to be tested. Two of the samples came in the field friendly dispensing method of double barrelled caulking gun, while the other DSTO#3 is a pot mixed sample.

A series of Flatwise tensile testing was conducted in order to determine the suitability of the three adhesives provided to solve the ongoing issue with the helicopter ballistic protection repairs. Samples with different adhesives, materials, surface preparation, cure time and environmental conditioning were tested to deem suitability of the adhesive.

B. Significance of Research

The ballistic panels are essential for the protection of the members on board the helicopter and are part of the aircraft airworthiness in a deployed location. This research is vital to find a new adhesive for the repair of panels while deployed in the field environment. A new adhesive will also ease the logistical chain and possibly assist in saving the Australian Aviation Corps money on their current repair program.

C. Literature Review

The literary review has considered the relevant literature available for the topic at hand: adhesives for the field repairs of ballistic protection panels. Since no adhesive has proven to meet the baseline, the literary review as part of the initial report has presented the principles behind adhesion and adhesive bonding. It has also considered aramid as a material since the material was highlighted as the biggest issue in the panels serviceability.

Previous research found PRC 1440 and EA9309 were unsuited (Attachment A in [1]). DSTO also tested Collano 22.000 film adhesive, EA9309, CB200 and SLS100/200 they were all deemed unsuitable [1]. The tests conducted in this area at DSTO have used the load rate of 0.5mm/min for all flatwise tensional tests. Hence this is the rate used for the conduction of my thesis to be comparable to the DSTO results.

Figure 1. Flatwise tensile strength testing set up
II. Methodology

Flatwise tensile strength testing as can be seen in Fig 1 below (ASTM C297/C297M -04) was conducted using an Instron 1185 and 5500R test machine. The testing was broken up into different areas of interest; benchmark study, different materials, surface preparation, cure time and environmental conditioning. In all cases minus the cure time study the adhesive had reached full cure.

A. Field Environment

The field environment implies a lack of time available for cleaning and curing, as well as resources normally available in a laboratory or aircraft maintenance hangar. In order to generate useful results for the Australian Army it was decided the most basic level of surface preparation should be applied, in order to replicate those conditions found in a field environment. The field environment limits the materials and process available for surface treatment; therefore no limited surface treatments are available. This will reduce the quality of the bonds; with the Aramid unable to undergo plasma treatment and aluminium unable to be grit blasted. The Army Aviation Systems Program Office have confirmed that solvents such as MEK are still available in this environment. Although it is not engineering best practise to use only solvent cleaning and mechanical abrasion (Scotch-Brite) using this method for this thesis would accurately replicate the environmental conditions that are present within the field environment. This type of treatment has been developed through DSTO and is called Minimum Surface Treatment (MST) [2].

B. Adhesives

The adhesive samples provided by ACE are polyurethane based adhesives. All samples form a thixotropic paste when mixed this allows for thick coats to be applied to vertical surfaces or the underside of horizontal surfaces, making it highly desirable for a field environment. The adhesives can be stored for 12 months at temperatures of 20 degrees meaning an air-conditioned venue is all that is required. The product data sheets and other information can be found in Appendix A.

DSTO #1 and DSTO #2 were both provided in cartage kits requiring only a double barrelled caulking gun to dispense Part A & B of the adhesives. This dispensing method is highly desirable for the field as it does not involve precise mixing and measuring equipment unlike DSTO #3. DSTO #1 is a 1:1 mix whereas DSTO #2 is a 2:1 mix. The working life of the mixed adhesive is 15 – 30 minutes which is sufficient although not plentiful for most field repairs.

DSTO #3 is a three part mix, the kit is made such that all parts can be added to the Part A tin and mixed. Although DSTO#3 is convenient, if smaller amounts are needed for the repair the portions off A, B and C need to be weighed accurately to the ratio of 100:23:2.4, which is not ideal for the field environment. The working life of DSTO #3 is 30 - 40 min at room temp which is sufficient for most repair applications.

Although DSTO #3 is workable in a field environment DSTO #1 or #2 would be preferred if results are comparable as ‘they are more user friendly’.

C. Test Samples

The test specimens were all 50 mm x 50 mm. A total of one hundred and eleven specimens were prepared for this project. Standard samples were prepared in the following way and are illustrated in Fig 2 below:

- Aluminium test blocks - MEK wiped and Scotch-Brite
- Aramid fibre (Aramid side) – MEK wiped, Scotch-Brite and nitrogen spray clean
- Ceramic tile – MEK wiped, Scotch-Brite and nitrogen sprayed clean
The multi-ply samples were prepared as per Fig 2 however a multi-ply Aramid layup was used instead of a sheet. In the material study of ceramic grit blasting was used along with another adhesive on the aluminium to ceramic bond as that substrate combination doesn’t occur in the panels. Figure 3 above shows a ceramic sample setup. The aluminium samples used for the aluminium material study were prepared as per the standard sample preparation above and the adhesive applied between the two aluminium blocks.

In the solvent samples MEK was replaced by either acetone or distilled water. For the environmental conditions study, the samples were prepared as per normal with only humidified Aramid samples (70 degrees at 95% relative humidity) used. For all test specimens besides those are four and six hours the adhesives were cured for at least twenty four hours or until full cure.

D. Testing Procedure

The experiments were conducted on the Instron 1185 and 5500R test machines at the DSTO in Fishermans Bend, Victoria. The test machines are single column testing machines suitable for tension and compression applications with 100KN load cells, which can be programmed to suit the user’s specific test using the Bluehill 2® software. The Instron 1185 test machine can be seen in Fig 4 below. The crosshead speed used in this testing was 0.5 mm/min for all specimens. The load, crosshead displacement and time were measured and recorded for all specimens.

Figure 2. Standard specimen with Aramid.

Figure 3. Specimen with Ceramic tile.

Figure 4. The experimental set up of the Instron 1185 test machine
E. Result Processing
Besides direct measurement of the load, time and sample area, the pressure experienced by the sample at time of failure was obtained. The standard deviation and percentage error were calculated from the average of each set. In addition to this, raw data collected from the Instron machine was inputted into excel and the Figures below in the results section were generated. The generated graph data was used to determine the stiffness of the system for each sample.

III. Analysis of Results

For each sample and study type the following type example of a graph and table were produced as seen in Fig 5 and Table 1 below. These where created for all of the one hundred and eleven samples before the comparison graphs seen and discussed below in sections A-E where created. The samples are compared to the 1.74 MPa baseline, accounting for the 50 mm x 50 mm samples this means a minimum max force of 2.35 KN.

Table 1. Acetone and DSTO#1 data table

<table>
<thead>
<tr>
<th>Sample</th>
<th>Adhesive</th>
<th>Peak load (KN)</th>
<th>Peak Pressure (MPa)</th>
<th>Stiffness (Gpa)</th>
<th>Failure ext (mm)</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 # 1</td>
<td>5.84</td>
<td>2.34</td>
<td>12.15</td>
<td>0.81</td>
<td>Adhesive</td>
<td></td>
</tr>
<tr>
<td>41 # 1</td>
<td>6.91</td>
<td>2.76</td>
<td>12.13</td>
<td>0.65</td>
<td>Adhesive</td>
<td></td>
</tr>
<tr>
<td>42 # 1</td>
<td>6.86</td>
<td>2.74</td>
<td>11.65</td>
<td>0.68</td>
<td>Adhesive</td>
<td></td>
</tr>
<tr>
<td>43 # 1</td>
<td>4.88</td>
<td>1.95</td>
<td>11.19</td>
<td>0.55</td>
<td>Adhesive</td>
<td></td>
</tr>
<tr>
<td>44 # 1</td>
<td>5.89</td>
<td>2.36</td>
<td>13.79</td>
<td>0.54</td>
<td>Adhesive</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>6.08</td>
<td>2.43</td>
<td>12.18</td>
<td>0.64</td>
<td>Adhesive</td>
<td></td>
</tr>
</tbody>
</table>

Standard deviation σ 0.84 0.34 0.98 0.11

Figure 5. Acetone surface preparation and DSTO #1 load versus extension graph

A. Benchmark Study
The samples for the Benchmark study used the configuration seen in Fig 2 above. The results seen below in Fig 6 show that DSTO#2 is not suitable for the needs of this study as it is below the baseline cut off of 2.35KN. CB 200 although it averaged being above the baseline of 2.35KN has a large error range due to inconsistent nature. Therefore CB 200 is also unsuitable for this study. As this was the first study conducted this meant that both CB 200 and DSTO#2 where used for no further studies. Both DSTO#1 and DSTO#3 maximum average load including error bars met the baseline, these two adhesives where then used for the reminder of the study. Although it should be noted that DTSO#3 performed better in this application.
B. Different Materials

The results of the material study shown below in Fig 7 demonstrate that both DSTO#1 and #3 are able to adhere to the silicon carbide (ceramic) tiles and the aluminium sheets to the required standard. DSTO#1 surprisingly had a lower maximum average force than expected when adhered with aluminium. This result is unable to be explained by the author and due to the low percentage error it is assumed that it is an adhesive issue over a preparation issue. Figure 7 also highlights the large error bars seen in the ceramic tile data for both adhesives. These larger error bars are due to the surface treatment proving to be quite ineffective on the hard surface of ceramic. Although an error this large is normally a concern in the scope of this project it is acceptable and will not impact on the outcome required by Army Aviation. It can be seen in Fig 7 that DSTO#3 is significantly better at adhering to aluminium than DSTO#1, while it preformed slightly worse with silicon carbide tiles.

C. Surface Preparation

Figure 8 below shows clearly that the stronger the solvent the greater the bond strength achieved as expected. It is interesting to note that even with only distilled water used as the cleaning solvent, the bond strength still remained above the baseline for both adhesives with errors accounted. DSTO#1 with distilled
water solvent failed in a differing manner to the other samples, the distilled water solvent samples experienced failure at the Aluminium interface. This result is not surprising considering the low solvent strength of distilled water and DSTO#1 and Aluminium interactions being poor as seen in Fig 7 above. These results lead to the conclusion that water is unsuitable for the solvent for cleaning in the field environment and also it confirms the concerns that distilled water may be unable to remove some contaminants during the cleaning process. Figure 7 also demonstrates how with all three solvent DSTO#3 outperformed DSTO#1.

The use of Acetone for the solvent for these types of repairs is recommended as it has a lower risk to those exposed and is generally safer to work with. Figure 8 below also highlights that although performing to a lower standard than MEK it is more than suitable for the field environment application because it performs well above the baseline standard.

![Figure 8. Average Maximum load graph for differing surface preparations](image)

D. Cure Time

From Table 2 below you can see that there were some issues in the timings with these samples. For the four hour DSTO#1 samples there was a delay in the availability of the testing machine, this lead to a roughly 4 hour and 40 minute cure. The delay with the six hour DSTO#1 samples originating from a software issue with the computer connected to the testing machine, this lead to a six hour and 18 min cure on average. Both these timing issues where beyond the author’s control and Table 2 is provided to allow the data to be as accurate as possible. There was no issue with the timing of the DSTO#3 samples as can also be seen in Table 2.

<table>
<thead>
<tr>
<th>Surface Prep</th>
<th>Average Max Load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MST #1</td>
<td>8.7</td>
</tr>
<tr>
<td>MST #3</td>
<td>8.5</td>
</tr>
<tr>
<td>Acetone #1</td>
<td>6.2</td>
</tr>
<tr>
<td>Acetone #3</td>
<td>6.0</td>
</tr>
<tr>
<td>Water #1</td>
<td>5.8</td>
</tr>
<tr>
<td>Water #3</td>
<td>5.6</td>
</tr>
</tbody>
</table>

**Table 2 – Exact Cure Times**

<table>
<thead>
<tr>
<th>4 hour Samples</th>
<th>Actual time</th>
<th>6 hour Samples</th>
<th>Actual time</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSTO#1 - 87</td>
<td>4 h 46 min</td>
<td>DSTO#1 - 99</td>
<td>6 hr 23 min</td>
</tr>
<tr>
<td>DSTO#1 - 88</td>
<td>4 h 40 min</td>
<td>DSTO#1 - 100</td>
<td>6 hr 20 min</td>
</tr>
<tr>
<td>DSTO#1 - 89</td>
<td>4h 39 min</td>
<td>DSTO#1 - 101</td>
<td>6 hr 18 min</td>
</tr>
<tr>
<td>DSTO#1 - 90</td>
<td>4h 39 min</td>
<td>DSTO#1 - 102</td>
<td>6 hr 15 min</td>
</tr>
<tr>
<td>DSTO#3 - 91</td>
<td>4h 01 min</td>
<td>DSTO#3 - 103</td>
<td>6 hr 12 min</td>
</tr>
<tr>
<td>DSTO#3 - 92</td>
<td>4h</td>
<td>DSTO#3 - 107</td>
<td>6 hr 02 min</td>
</tr>
<tr>
<td>DSTO#3 - 93</td>
<td>3 h 59 min</td>
<td>DSTO#3 - 109</td>
<td>6 hr 01 min</td>
</tr>
<tr>
<td>DSTO#3 - 94</td>
<td>4 h 01 min</td>
<td>DSTO#3 - 110</td>
<td>5 hr 59 min</td>
</tr>
<tr>
<td>DSTO#3 - 95</td>
<td>3 h 59 min</td>
<td>DSTO#3 - 111</td>
<td>5 hr 57 min</td>
</tr>
</tbody>
</table>
From Fig 9 below it can clearly be seen that at both four and six hours DSTO#3 is unsuitable and unable to meet the 2.35KN baseline. At the time of testing DSTO#3 was still quite ‘tacky’ and appeared undercured also at the four hour testing mark it was still omitting odours and gloves where used for handling tested samples.

DSTO#1 at both testing points appeared cured, it was less ‘tacky’ at the six hour mark. From Fig 9 below it can be seen that at the four hour test point the adhesive was quite close to the baseline although because of other errors, it would not meet the standard required. At this stage it was deemed to be at a 29.5 % cure as compared to benchmark study. It can also be seen that at the six hour test point the adhesive easily overcame the baseline and is deemed suitable for the application. At the six hour point the adhesive had reached a 76.4 % cure as compared to the data point from the Benchmark Study of section A. Following this it is then recommended that further testing be conducted at five and a half hours in order to deem if the cure time can be shorted to that time frame.

![Cure Time](image)

**Figure 9. Average maximum force for different cure times**

E. Environmental Conditioning (Humidity)

The samples were placed in a humidity chamber at 70 degrees Celsius and 95% relative humidity until they had fully wetted out. They were removed from the chamber and prepared as per all other samples. Figure 10 below shows that even with a humid environment both adhesives meet the baseline and are acceptable for use. DSTO#1 preformed slightly better than DSTO#3 on average although it error was larger. Figure 10 also highlights the fact that the average maximum load capacity has been reduced by 2-3 KN on average when compared to Fig 6.

Although humidity plays an effect on the performance of these adhesives it is not deemed a sufficient risk to the integrity of the planned repairs. The environmental conditions that these repairs will operate in should not exceed the tested conditions.
IV. Discussion

A. Adhesive comparison

From Fig 11 above it can be seen that DSTO#1 preforms above the baseline for all samples except for the four hour cure sample which with errors is below the 2.35 KN cutoff. It is also of note that water used as the solvent in the surface preparation although it does have errors, is considered to meet the baseline. Although it is very close to the baseline, it could not be recommended because in a realistic field environment errors are likely to be larger. DSTO#1 provided suitable in all areas of this testing to some degree.
Figure 12. Comparison of maximum load for all tests performed with DSTO#1

Figure 12 above demonstrates how the results obtained for DSTO#3 where all above the baseline (with errors considered) minus both the four and six hour cure samples. These results are not beneficial to the Australian Army as the shorter the maintenance and repair time is, the more use the helicopter is to them strategically.

When both Fig 11 and 12 are considered it can be seen that DSTO#3 is generally of a higher adhesive strength than DSTO#1. The fact that DSTO#1 can withstand a lower cure time before meeting the baseline makes it strategically and practically more desirable for the Australian Army. DSTO#1 also has the advantage of not requiring the use of scales or extra equipment in its preparation unlike DSTO#3. DSTO#1 is in a double barreled caulking gun and simply requires a clean surface to mix on before application can occur. DSTO#3 requires precise measurement of its three parts to the required mix ratio and then mixing within a cup or similar vessel before application. Considering the presented information in Fig 11 and 12 above DSTO#1 is more practical for Army Aviation needs.

B. Discussion of Errors

There is considerable opportunity for error to have occurred during the course of the project. Error can be minimised but unfortunately they cannot be avoided completely. Therefore the experiments were carried out in a controlled set up in order to minimise the error that may have arisen as a consequence of the experimental set up. The samples and adhesives were kept in a constant temperature environment unless a part of the environmental study samples.

The mechanical testing carried out in the laboratory was undertaken with the relevant apparatus mentioned in the previous section and the appropriate calibrations were made each time an experiment was carried out. Although an effort was made for each experiment to ensure that the setup and preparation was identical, it is apparent that the prospect of error in such a case is unavoidable. The surface preparation was the biggest variable in error in the sample preparation, this effect can be seen in Fig 7 with the ceramic samples a large error bar. The biggest variable in error in the ceramic sample preparation is from the material being quite hard and the Scotch-Brite having little effect on the surface roughness. Although in the general case it can be seen in sample 43 of Fig 5 and Table 1. This sample was lower than the other samples and although failing in the same way hence it is probably that a different pressure during scotch-Brite application could have been the simple difference.
V. Conclusions

From the results presented in this report it can be seen that both DSTO#2 and CB 200 are unsuitable for the Army Aviation’s needs. DSTO#2 doesn’t meet the baseline cut off and CB200 has a large error margin and is not consistent. Both DSTO#1 and DSTO#3 meet the baseline standard for Aramid with MST, acetone and distilled water surface preparations, humidity, aluminium and silicon carbide tiles.

Although DSTO#3 generally performs to a higher maximum load than DSTO#1, it is less user-friendly. DSTO#3 is a three part pot mix and harder to use in a field environment due to the need of precise measurement over the double barrelled corking gun option of DSTO#1. Also DSTO#1 can achieve the required baseline with a lower cure time than DSTO#3 making it more applicable for Army Aviation. Therefore it is recommended that DSTO#1 be used to fulfil the needs of Army Aviation.

VI. Recommendations

Given the research that has been conducted that the following be considered as further research into DSTO#1 and #3:
1. A temperate study could be conducted.
2. Further investigation into cure time to see if five and a half hours is suitable for Army Aviation’s needs with DSTO#1.
3. Beyond this more research in an effective way to remove the Collano film layer on the top of the Aramid fibre while still using MST methods would also be beneficial.

Acknowledgements

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References