Adhesive Bonding Methods for Integrating Macro-fibre Composite Elements onto Carbon-Fibre Composites Aircraft Structures for Strain Energy Harvesting

Qiang Li, Yang Kuang and Meiling Zhu*

College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, UK

*Corresponding author: m.zhu@exeter.ac.uk

Abstract. As an innovative piezoelectric transducer, the Macro-Fibre Composite (MFC) has been widely adopted in aviation and aerospace industries acting as generators for Energy Harvesting (EH) and actuators for controlling vibration, noise, and deflections in composite structures. Generally, the MFC element must be bonded onto host structures with adhesive, and the performance of the bonded MFC element is significantly dependent on the bonding quality. In this work, four different adhesive bonding methods based on mechanical clamping and vacuum-bagging were explored according to particular application scenarios. In order to provide reference for the integration of MFCs onto composite structures under different application scenarios, the performance of MFC element acting as a strain energy harvester bonded with different methods was compared and discussed.

Key words: Piezoelectric energy harvesting, Macro-Fibre composite, vacuum bagging, adhesive bonding

1. Introduction

The Macro-Fibre Composite (MFC) developed by NASA has been widely used as actuators, sensors and energy harvesters due to its extreme flexibility and durability together with high piezoelectric performance compared with the traditionally piezoceramic materials. The flexibility of the MFC allows it to be bonded onto engineering structures that have flat as well as curved surfaces without fear of accidental breakage. One of the applications of MFCs as energy harvester is to harvest the strain energy from aircraft wings to power wireless sensors for aircraft structural health monitoring [1, 2]. Generally, the MFCs can be adhesively bonded onto the host structures with epoxy adhesive for the purpose of strain energy harvesting and the bonding quality will affect the energy transfer efficiency from the host structures [3]. In order to obtain a good bonding quality, an evenly pressure should be applied onto the top surface of the MFCs and a proper epoxy curing process is needed to improve the bonding quality. Mechanical bonding and vacuum-bagging are two commonly methods to apply clamping pressure for the adhesive bonding of MFCs. The mechanical bonding can easily generate high clamping force but hard to apply evenly pressure onto a complicated structure. The vacuum-bagging can keep good performance for complicated structures without additional costs and operations but it usually needs additional equipment such as an autoclave to apply higher pressure than atmospheric pressure. Moreover, the bonded MFC together with host structures should be put into an autoclave for the curing of epoxy adhesive under particular temperature and pressure. However, this can be difficult if the MFCs have to be bonded onto already-manufactured aircraft components due to the large size or the component integrated with elements unsuitable for heating. Therefore, it is necessary to explore the proper adhesive bonding method by considering the limits and requirements of varieties application scenarios.

In this work, four adhesive bonding methods including Mechanical Bonding (MB), Vacuum-bagging & curing within autoclave (VBIA), Vacuum-bagging & curing out-of-autoclave (VBOA), and Vacuum-bagging & co-curing within autoclave (VBCA) were implemented for the adhesive bonding of MFCs. Further, the performance, as strain energy harvesting, of the MFCs bonded with above methods was evaluated for the reference of different application scenarios. Based on the experiment results, the suitable adhesive bonding method for integrating MFCs onto the composites structures was recommended according to particular application scenarios.

2. Experiment Procedure

Five pieces of MFCs (MFC M8528-P2 Smart Material Ltd.) were individually bonded onto five carbon fibre composite beams with a particular bonding method. The composite beams (length×width×thickness: 300×50×5 mm³) were made of aerospace grade carbon fibre epoxy Prepreg IM6/950 which lay-up with stacking sequence [45°/0°/-45°/90°]. The epoxy adhesive DP460 produced by 3M™ was adopted for the bonding of MFCs and the MFC was bonded onto the middle of the beam’s top surface. The four adhesive bonding methods used in this work are described as follows:

- **Mechanical Bonding (MB):** the MFC was pressed onto the surface of the composite beam with G-clamps during curing within autoclave under 70°C for 3 hours.
- **Vacuum-bagging & curing within autoclave (VBIA):** the MFC was pressed onto the surface of the composite beam via vacuum bagging and cured within autoclave under 70°C for 3 hours. The pressure applied in autoclave during curing is 30 psi and 60 psi respectively for two different samples.
- **Vacuum-bagging & curing out-of-autoclave (VBOA):** the MFC was pressed onto the surface of the composite beam via vacuum bagging and a flexible heat blanket was enveloped within vacuum
bag to apply heat during curing under 60°C for 2 hours. The curing process was completed out-of-autoclave under atmospheric pressure of 14.7 psi.

- **Vacuum-bagging & co-curing within autoclave (VBCA):** the MFC was placed onto the top of the first ply of the carbon fibre epoxy prepreg lay-up with stacking sequence of [45/0/2/-45/2/90] and co-curing within autoclave under 125°C with pressure of 90 psi for 3 hours.

The five MFC samples adhesive bonded with different methods were tested on a material testing machine (INSTRON E10000) as shown in Fig 1. A sinusoidal force with different frequencies was applied on the beam to induce a sinusoidal strain with peak-to-peak amplitude of 600 µε. The sinusoidal force was biased so that the beam was always in tension. A load resistor was connected with the electrodes of the MFC. As a result of the induced strain, a voltage was generated across the load resistor, which was measured by a data log to calculate the power output.

![Sample Bonding Method & Curing Conditions](image)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Bonding Method &amp; Curing Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFC_1</td>
<td>MB, 70°C for 3 hours</td>
</tr>
<tr>
<td>MFC_2</td>
<td>VBOA, 60°C, 14.7 psi, 2 hours</td>
</tr>
<tr>
<td>MFC_3</td>
<td>VBIA, 70°C, 30 psi, 3 hours</td>
</tr>
<tr>
<td>MFC_4</td>
<td>VBIA, 70°C, 60 psi, 3 hours</td>
</tr>
<tr>
<td>MFC_5</td>
<td>VBCA, 125°C, 90 psi, 3 hours</td>
</tr>
</tbody>
</table>

Fig 1 Experiment Set-up

![Fig 2 Comparison of power output under peak-to-peak strain of 600µε](image)

3. Results and Discussions

The experimental results, as shown in Fig 2, suggested that the mechanical bonded MFC presents the best performance on energy harvesting (0.98mW and 4.95mW at 2Hz and 10Hz, respectively). This is mainly because a high press force can easily be applied onto the MFC via mechanical clamping to achieve a thin epoxy adhesive layer between MFC and composite beam structure. The power outputs of MFCs bonded via VBCA and VBOA are 16.5% and 22.5% lower, respectively, than the MFC bonded via MB method. The performance of MFCs bonded via VBIA method depends on the curing conditions where higher curing pressure lead to a better performance. However, the power output of MFC bonded via VBIA with 60 psi is 15.8% lower than the MFC bond via VBOA with 14.7 psi. This is because the VBOA method is capable of avoiding air bubbles and obtaining an even adhesive layer through a continuous vacuum condition during curing under high temperature.

The adhesive bonding methods explored in this work should be proposed depends on the particular application scenarios. MB method can obtain high bonding quality through applying high press force for the integration of MFC onto a flat composite structure but it will become hard or impossible when the host structures has a complicated surface geometry. Vacuum-bagging based bonding methods can keep good performance for complicated structures without additional costs and operations. However, for host structures that are already-manufactured or not suitable for curing within autoclave such as an aircraft wing, the VBOA will be an ideal method for the integration of MFCs.

4. Conclusions

In this work, four type of adhesive bonding methods used for the integration of MFCs onto composite structures were implemented. The performance of MFCs, acting as strain energy harvesters, bonded with different methods was evaluated through comparing their power output under the same strain level. Based on the results, the VBOA method should be an ideal method for the adhesive bonding of MFCs onto complicated composite structures.

Acknowledgement: This work is supported by EPSRC grant through En-ComE project (EP/K020331/1)

References