Application of Vibration Monitoring to Detect Flaws in Stiffened CFRP Panels

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With the increase in the use of composite materials, in a wide range of industries, the complexity of the structures being manufactured is also increasing. There are many different methods of detecting damage using conventional non-destructive inspection techniques, but not all damage is detectable with these methods. Vibration monitoring is a damage detection technique that can be used as part of a Structural Health Monitoring System or event based to detect flaws at predetermined times. In this study four CFRP stiffened panels are fabricated with and without damage in the form of disbonds between the stiffeners and the base plates. Vibration monitoring is used to detect shifts in the frequency response between the panels. This report will detail the steps taken to analyse and evaluate vibration monitoring as an effective tool to detect common damage such as disbonds and delaminations in stiffened CFRP panels.

Contents

I. Introduction 2
II. Design and Fabrication 2
III. Mechanical Testing 3  
   A. Three-Point Bending Setup and Method 3  
   B. Stiffened Panel Three-Point Bending 4  
   C. Summary 4
IV. Vibration Monitoring 4  
   A. Experiment Setup 4  
   B. Method 4  
   C. Stiffened Panel Testing 5  
   D. Summary 6
V. Conclusions 9
VI. Recommendations 9

Acknowledgements 10
References 10

1 PLTOFF, School of Engineering & Information Technology. ZEIT4501.
I. Introduction

Failure of a structure or component while in service can have costly consequences and can even lead to catastrophic results. There are various techniques currently available that are aimed at reducing the chance of failure occurring. These methods include non-destructive inspection (NDI) and damage tolerant design[1]. Unfortunately, failures due to manufacturing or serviced induced flaws do occur, even with strict guidelines and procedures in place to minimise the risk. This thesis report will describe the evaluation of vibration monitoring to determine if it can be used in concert with the aforementioned procedures to further reduce the chance of failure occurring.

NDI techniques in use in the manufacturing and service industries range from simple visual inspections to costly and potentially dangerous gamma ray inspections. Not all of these inspections can be used for all types of defects in all types of materials. The material used in this project is carbon fibre reinforced polymer (CFRP) which is fabricated into a stiffened panel assembly. The more common fabrication and in-service defects that occur in this type of structure are delaminations and disbonds[2].

Inspections for delaminations and disbonds in Carbon-Fibre Reinforced Polymer (CFRP) laminates are typically performed using Ultrasonic Inspection. Thermography and holography are emerging technologies that are used in some industries and are currently being developed for further use. These three techniques are useful in particular circumstances and when used in combination can detect a large percentage of subsurface flaws. The disadvantage in these methods is that it is difficult to detect disbonds that occur between stiffeners, such as stringers, and the panel or door that they are bonded to. It is also difficult to detect damage in inaccessible areas.

Vibration monitoring is a technique that uses certain inherent physical properties of the structure, such as the natural frequency, to determine if flaws are present. This technique is not restricted by the physical layout of the structure and as such tends to be a useful technique to detect flaws where they have previously been difficult to find.

The goal of this thesis project was to investigate the viability of utilising vibration monitoring to detect flaws such as disbonds in stiffened FRP composite panels. The aim of this report is to provide a detailed account of the thesis project including a description of the fabrication method, the testing methods employed, and conclusions and recommendations.

This thesis report is divided into six sections: Section II contains details regarding the design and fabrication. Section III covers mechanical testing of the stiffened panels. Section IV details the procedures and results from the vibration testing component of the project. Finally, sections V and VI cover the conclusion and recommendations respectively.

II. Design and Fabrication

The stiffened panels were designed based upon considerations detailed by Niu[3], for general CFRP fabrication, and Howe[4], for stringer sizing and stiffener configuration (Fig. 1). The base of each of the panels has sides of 280 mm length. Bonded to the upper surface of this base plate are six L-shaped stringers bonded back-to-back to form three stiffeners. The ends of the free flanges of the stiffeners were tapered to allow for a smooth transition of the stiffener load into the skin. This feature was incorporated to prevent peel force / stiffener runout[5] during mechanical property testing. Each section of the panel was fabricated from four plies of CF0302/ VTM264 prepreg which is a 199 gsm 2/2 twill carbon fabric combined with an epoxy resin matrix[6]. The plies were oriented [0/90]s.

Each part of the panel was fabricated separately using an elevated temperature cure cycle with a ramp rate of 3°C per minute to 120°C for a 1 hour dwell time (Fig. 2). The stiffeners were bonded to the panel, and each other, with West Systems 105C epoxy / 206C hardener using a cold cure. Artificial disbonds were created by inserting an ETFE patch (Vac-Pak A6200[7]) between the middle stiffener and the plate (Fig. 3). Two panels were fabricated with this patch, one of 40 mm length and the other of 180 mm length. Both patches had a width equal to that of the middle stiffener under which it was inserted. No epoxy resin was used...
for bonding the stiffener to the panel in the patch region. Four panels were fabricated in total: one undamaged, two with artificial disbonds, and one without the middle stiffener which represented a panel with a full disbond.

III. Mechanical Testing

The aim of this phase of the study was to make a comparison between the bending stiffness values of each sample. The purpose for this comparison is to demonstrate that there is a measurable difference between plates; this is necessary for the next phase which involves vibration monitoring. The fabricated plates have very close physical properties such as the dimensions, type of material, method of fabrication and mass. The significant difference between them is the artificial damage introduced between the centre stiffener and the flat base plate. If there were no measurable differences in stiffness between the plates, and with all other physical properties being similar, it would not be guaranteed that measurable changes in frequency would be obtained during vibration monitoring.

Three-Point bending was chosen as the method for determining the mechanical properties of the stiffened plates due to the ease of setup and testing. Testing the samples in tension, compression, or shear would require a complicated fixture to support the stiffened plate. ASTM D5934 - 02 was selected as the test method as it was the only three-point bending test in the ASTM range that did not require failure of the test piece or temperature variation to determine the mechanical properties. This standard is used to determine the modulus of elasticity for rigid and semi-rigid plastic specimens[8]. This standard describes the procedure to perform three-point bending using a controlled rate of loading mechanical instrument. This test is used to assess the effects of different types of processing, the behavioural properties of resins (including cure), the effects of ply orientation on modulus, and the effects of additives from the fabrication process.

A. Three-Point Bending Setup and Method

Three-point bending was performed on the Shimadzu AG-X Plus 50kN Precision Universal Tester. The loading nose and lower support rollers were designed and fabricated specifically for these stiffened panels as the standard test apparatus was suitable for coupon size samples only. Figure 4 is an image of the undamaged stiffened panel undergoing three-point bending.

\[
\text{Stress} = \sigma = \frac{3FL}{2bd^2} \quad (1)
\]

\[
\text{Strain} = \epsilon = \frac{6Dd}{L^2} \quad (2)
\]

\[
E_B = \frac{\sigma}{\epsilon} = \frac{3FL}{2bd^2} \quad (3)
\]

Where:
- \(E_B\) = modulus of elasticity in bending (Pa),
- \(L\) = support span (m),
- \(b\) = width of beam tested (m),
- \(d\) = depth of beam tested (m),
- \(D\) = deflection of the beam (m), and
- \(F\) = force (N).

The elastic modulus for bending was determined to be 46 ± 1 GPa. This value is comparable to the values published by the material supplier: 60.0 GPa for tensile modulus at 0°; 60.5 GPa for tensile modulus at 90°; 54.0
GPa for compressive modulus at 0°; and, 53.0 GPa for compressive modulus at 90°[6]. The average stiffness of the flat plate was determined to be 3000 ± 80 N/m.

B. Stiffened Panel Three-Point Bending

Table 1 displays the results obtained from experimental testing of the stiffened panels. There was a large spread of results for the panel with the 180 mm disbond. One possible reason for this spread is that the non-rolling loading nose can introduce slight longitudinal forces and resisting moments in the specimen which superpose with the intended loading[9]. The panel was tested in the two possible orientations with both positions providing consistent results for that position but with a large difference between each position. Figure 5 displays the force and displacement curve for the fourth test performed on the panel with a simulated total disbond.

<table>
<thead>
<tr>
<th>Description</th>
<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Mass (g)</th>
<th>Support Span (mm)</th>
<th>Average Stiffness (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undamaged</td>
<td>280</td>
<td>280</td>
<td>239.6</td>
<td>230</td>
<td>67 000 ± 2000</td>
</tr>
<tr>
<td>40 mm Disbond</td>
<td>280</td>
<td>280</td>
<td>234.6</td>
<td>230</td>
<td>57 100 ± 800</td>
</tr>
<tr>
<td>180 mm Disbond</td>
<td>280</td>
<td>280</td>
<td>232.6</td>
<td>230</td>
<td>63 000 ± 6000</td>
</tr>
<tr>
<td>Total Disbond</td>
<td>280</td>
<td>280</td>
<td>186.4</td>
<td>230</td>
<td>51 000 ± 100</td>
</tr>
</tbody>
</table>

C. Summary

The three-point bending experiments have demonstrated that there is a reduction in stiffness for the panels with the artificial disbond. The panel with the 180 mm disbond will require further testing to reduce the margin of uncertainty; another form of three-point testing where the panel is brought to failure may be required to improve the accuracy.

IV. Vibration Monitoring

The method employed for vibration monitoring in this thesis is the Frequency Method. The natural frequencies of the panels are measured and a comparison is made between each panel to determine if the known damage is detectable.

The main reasons that this method was chosen was the ease with which the testing can be performed. This ease of testing translates to the ease of its use in a real life situation such as in the SHM on an aircraft. Low weight, inexpensive sensors can be incorporated into a system that is integrated within the aircraft sub-systems. This method would be based on the comparison of an undamaged structure to that of a structure that has suffered some form of damage.

The following sections will detail the methods used to perform vibration monitoring on the stiffened plates.

A. Experiment Setup

The experiments were conducted by suspending the test piece, by string from its upper corners, from a solid frame as depicted in Figure 6. This arrangement was used to simulate an all edges free boundary condition (FFFF). This method was chosen as opposed to clamping in a cantilever condition as special tooling would need to be manufactured to clamp the plate around the stiffeners.

Measurements were performed using the Polytec PSV-400 which is a non-contact scanning laser Doppler vibrometer. The laser Doppler vibrometer is a very precise optical transducer used for determining the vibration velocity and displacement at a point by sensing the frequency shift of back scattered light from a moving
surface. The software used was the Polytec PSV8.7 which enabled the extraction of natural frequencies and mode shapes from each test. The vibrometer was mounted on a tripod 2 m from the test piece with the lens normal to the front face of the plate.

Excitation was provided by a loudspeaker positioned 40 mm behind the test piece.

B. Method

Testing was performed with the loudspeaker providing excitation with a sweep signal from 0 Hz to 2000 Hz in 1.6s. The laser vibrometer measured the velocity at 120 different points on the plate throughout the range of excitation frequencies. 3200 lines were selected for the fast Fourier transform (FFT) grid which provided a resolution of 0.625 Hz. Each measurement was performed three times and averaged. The repetition of the test and the averaging of the measured results have the effect of improving the signal-to-noise ratio[10]. The stiffened plates were tested four times each in four different positions with the stiffeners oriented vertically in all tests: upright with stiffeners facing vibrometer, upright with flat surface facing vibrometer, inverted with stiffeners facing vibrometer, and inverted with flat surface facing vibrometer.

Each test produced a frequency response graph that depicted the velocity magnitude for the range of measured frequencies. The spikes in velocity are identified as the natural frequencies for the plate and are selected for further analysis. These frequencies were used to produce a 3D mode shape which is used to determine the type of deflection for that frequency. The mode shapes represent the effects on the structure by the excitation force such as bending, torsion, and in-plane motion, and a combination of these components[11]. In this instance the mode shapes are used to determine which natural frequencies are to be used for comparison between plates.

C. Stiffened Panel Testing

The natural frequencies obtained from the undamaged stiffened panel were used as the basis for determining if any damage was present in the other stiffened panels. Figure 7 displays the first eight mode shapes from the undamaged panel calculated from the frequency response. These mode shapes represent the magnitude of the vibration velocity with the white areas indicating zero velocity (node lines) through to the bright red regions which indicate the greatest magnitude.

Figure 7. Mode shapes for the undamaged stiffened panel.
Table 2 displays the measured results from all four stiffened panels. It is observed that the first two natural frequencies obtained from the panel with the total disbond are higher than those from the 180 mm disbond even though the stiffness of the panel is lower. This is a consequence of the reduction in mass from not having a middle stiffener; natural frequency is a function of mass and stiffness. This panel was 53.2 grams less than the undamaged panel for a 22.2% reduction.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Hz</th>
<th>Mode</th>
<th>Hz</th>
<th>Mode</th>
<th>Hz</th>
<th>Mode</th>
<th>Hz</th>
<th>Mode</th>
<th>Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undamaged</td>
<td>58.125</td>
<td>158.125</td>
<td>383.75</td>
<td>530</td>
<td>750</td>
<td>954.063</td>
<td>1108.13</td>
<td>1163.44</td>
<td></td>
</tr>
<tr>
<td>40 mm Disbond</td>
<td>58.125</td>
<td>143.75</td>
<td>388.125</td>
<td>505.625</td>
<td>689.375</td>
<td>811.406</td>
<td>916.875</td>
<td>1146.41</td>
<td></td>
</tr>
<tr>
<td>180 mm Disbond</td>
<td>50</td>
<td>136.25</td>
<td>156.25</td>
<td>331.875</td>
<td>470.469</td>
<td>823.906</td>
<td>940</td>
<td>1021.88</td>
<td></td>
</tr>
<tr>
<td>Total Disbond</td>
<td>51.875</td>
<td>148.125</td>
<td>183.75</td>
<td>276.25</td>
<td>349.063</td>
<td>434.688</td>
<td>663.125</td>
<td>821.875</td>
<td></td>
</tr>
</tbody>
</table>

D. Summary

The purpose of performing vibration testing on these stiffened panels is to determine if damage can be detected through shifts in natural frequencies. The frequency response of the plates has been measured; the next step is to isolate the frequencies relevant to the stiffness of the panels and use these frequencies as a point of comparison. Figure 8 displays the frequencies of all plates for an initial assessment.

Figure 8. Frequency response of all stiffened panels.

Shifts in frequency are visible in Figure 8 but it is difficult to determine what these shifts indicate due to the high concentration of peaks across the frequency range. An analysis of the mode shapes of each plate was required to determine the relationship between each plate. This analysis identified the mode shapes that are common to each of the stiffened panels. Table 3 displays the first common mode shape from each panel which is from the fundamental frequency of each one. All of these mode shapes have two vertical node lines with an identical shape to the 3D pattern. The magnitude of vibration velocity in the centre of each plate increases from the undamaged through to the plate with the total disbond which is representative of the condition of the stiffener. Cawley[12] suggests that the lowest frequency tends to be one which stresses the material chiefly in shear.

Table 3. First common mode shape for each stiffened panels.
The second mode shape for each panel is displayed in Table 4. The mode shapes for the first three panels have a similar pattern and magnitude of vibration velocity. The panel with the total disbond has a much higher velocity at the top and bottom edges along the centerline. The frequency for this mode decreases across the first three panels.

Table 4. Second common mode shape for each stiffened panel.

<table>
<thead>
<tr>
<th>Undamaged</th>
<th>40 mm Disbond</th>
<th>180 mm Disbond</th>
<th>Total Disbond</th>
<th>Mode Shape Drawing with Node Lines</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Mode 2" /></td>
<td><img src="image2" alt="Mode 2" /></td>
<td><img src="image3" alt="Mode 2" /></td>
<td><img src="image4" alt="Mode 2" /></td>
<td><img src="image5" alt="Node Lines" /></td>
</tr>
</tbody>
</table>

Table 5 displays the third common mode shape for each panel. This is the fourth and fifth mode for the panel with the 180 mm disbond and total disbond, respectively; they each have other mode shapes in their frequency response that are unique to those particular panels. This mode shape provides a clear picture of where the disbond is situated. In the undamaged panel the pattern is close to symmetrical running vertically down the panel. The 40 mm disbond panel has an indication of a break in the centre of the two middle green sections which coincides with the position of the ETFE Patch. Similarly for the plate with the 180 mm ETFE patch, there is a large break in the middle green sections. The plate with the total disbond displays a region in the centre vertical section which exhibits the highest magnitude of vibration velocity. This is due to not having the support of a stiffener.

Table 5. Third common mode shape for each stiffened panel.

<table>
<thead>
<tr>
<th>Undamaged</th>
<th>40 mm Disbond</th>
<th>180 mm Disbond</th>
<th>Total Disbond</th>
<th>Mode Shape Drawing with Node Lines</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image6" alt="Mode 3" /></td>
<td><img src="image7" alt="Mode 3" /></td>
<td><img src="image8" alt="Mode 4" /></td>
<td><img src="image9" alt="Mode 5" /></td>
<td><img src="image10" alt="Node Lines" /></td>
</tr>
</tbody>
</table>

Table 6 displays the final mode shape that is present with the panels that have three stiffeners. It is not present with the panel that has a total disbond. This is an indication that it is unique to panels fabricated to this design that have three stiffeners. Each pattern in this mode shape is similar with identical node lines and vibration velocity. The first two panels have a maximum velocity of between 3 to 5 \( \mu \cdot m/s \) and the third panel measures between 5 and 7 \( \mu \cdot m/s \).

Table 6. Forth and last common mode shape for each stiffened panel.

<table>
<thead>
<tr>
<th>Undamaged</th>
<th>40 mm Disbond</th>
<th>180 mm Disbond</th>
<th>Total Disbond</th>
<th>Mode Shape Drawing with Node Lines</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image11" alt="Mode 4" /></td>
<td><img src="image12" alt="Mode 4" /></td>
<td><img src="image13" alt="Mode 5" /></td>
<td>Not present</td>
<td><img src="image14" alt="Node Lines" /></td>
</tr>
</tbody>
</table>

From these common mode shapes, four natural frequencies from the undamaged panel have been identified to monitor for shifts in frequency. Shifts at these frequencies can be related to a reduction in stiffness due to the presence of a disbond. Figures 9 to 12 display the frequency responses in the range for the first four natural frequencies of the undamaged stiffened panel. In Figure 9, the natural frequency for the undamaged panel, indicated by the black line, peaks at 58.1 Hz. It is evident that there is a significant shift in frequency with the
panel with the 180 mm disbond, indicated by the green line, but the panel with the smaller disbond has not shifted, indicated by the red line. For the second natural frequency, Fig. 10, both artificially damaged panels show indications of a shift in natural frequency.

![Figure 9. Mode 1 Frequency shift comparison between the three stiffened panels.](image)

![Figure 10. Mode 2 Frequency shift comparison.](image)

The third natural frequency is displayed in Figure 11. The shift in the panel with the 180 mm disbond is significant, but the smaller damaged panel has increased slightly in frequency. The fourth frequency (Fig. 12) is similar to the second frequency; both damaged panels have a reduced frequency.

![Figure 11. Mode 3 frequency comparison.](image)

![Figure 12. Mode 4 frequency comparison.](image)

These frequency responses and the comparisons between each panel and the undamaged panel form the basis of the Frequency Method for vibration analysis. In a structural health monitoring system (SHM) these graphs would be monitored for any deviation away from the known natural frequencies of an undamaged panel. Table 7 displays the data obtained from these graphs. The row labelled shift represents the difference between that particular panel and the undamaged panel. The following paragraphs discuss the analysis of these results.

<table>
<thead>
<tr>
<th>Description</th>
<th>Undamaged</th>
<th>40 mm Disbond</th>
<th>180 mm Disbond</th>
<th>Total Disbond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (kg)</td>
<td>239.6</td>
<td>239.6</td>
<td>239.6</td>
<td>239.6</td>
</tr>
<tr>
<td>Mode A</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>58.1</td>
<td>58.1</td>
<td>50.0</td>
<td>51.9</td>
</tr>
<tr>
<td>Shift (%)</td>
<td>0.0</td>
<td>-14.0</td>
<td>-10.8</td>
<td></td>
</tr>
<tr>
<td>Mode B</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>138.1</td>
<td>143.8</td>
<td>136.3</td>
<td>148.1</td>
</tr>
<tr>
<td>Shift %</td>
<td>-9.1</td>
<td>-13.8</td>
<td>-6.3</td>
<td></td>
</tr>
<tr>
<td>Mode C</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>383.8</td>
<td>388.1</td>
<td>331.9</td>
<td>349.1</td>
</tr>
<tr>
<td>Shift %</td>
<td>1.1</td>
<td>-13.5</td>
<td>-9.0</td>
<td></td>
</tr>
<tr>
<td>Mode D</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>530.0</td>
<td>503.8</td>
<td>471.9</td>
<td></td>
</tr>
<tr>
<td>Shift %</td>
<td>-5.0</td>
<td>-11.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7. Tabulated data for the first four natural frequencies of all four panels.
40 mm disbond panel: There is no shift in the first mode, a 9.1% drop in frequency in mode 2, a slight increase of 1.1% in mode 3 and a 5% drop in mode 4. It is possible that these shifts are as a result of the artificial disbond; the reduction in stiffness is known to have an effect on individual natural frequencies or a combination of natural frequencies. In a composite structure such as these panels, this is due to their anisotropy and macroscopically heterogeneous nature[2]. Genta comments that due to the complex damping properties of a composite material, these materials often show strong dependence of mechanical characteristics with changing frequency[13]. In this instance the sample size is not large enough to make a definitive conclusion whether this shift is particular to this individual panel due to other factors such as slight property differences from fabrication or if it is due to the disbond.

180 mm disbond panel: There is a significant drop in all modes for this panel ranging from between 11 and 14%. It is concluded that these reductions in frequency are as a result of the disbond and its consequential reduction in panel stiffness.

Total disbond panel: There is a drop in frequency for the three common frequencies that is as a result of loss of stiffness in the panel from not having the middle stiffener. As previously discussed, the values are slightly higher than those of the panel with 180 mm disbond. This is due to the reduction in mass of the panel and the relation between mass, stiffness and frequency.

V. Conclusions

The aim of this project was to investigate whether damage in CFRP stiffened panels can be detected from changes in their natural frequencies. All four panels have a different level of stiffness as demonstrated by the mechanical testing of the panels. The experiments performed on the four stiffened panels have shown that there is a shift in frequency related to the change in stiffness of the panel. The shift in frequency is much more pronounced in the panels with the 180 mm disbond and the total disbond. It is possible that the two downward shifts in frequency on the panel with the 40 mm disbond were due to the reduction in stiffness, but further testing is required to make a definitive conclusion if this is the case.

It was established that the natural frequencies of the undamaged panel need to be determined to enable a frequency response based structural health monitoring system to be effective. In this particular case, the first four natural frequencies of the undamaged panel were monitored for shifts in frequency to detect damage. These frequencies were used as they were identified from their mode shapes as being common between panels. The panel with a total disbond only had three of these frequencies indicating that the fourth frequency is unique to a panel of this design with all three stiffeners present. Also, this panel had two additional natural frequencies between the second and third common frequencies. These additional frequencies could be present as a consequence of the difference in mechanical properties between this panel and the others. This feature is also present in the panel with the 180 mm disbond; it has one additional natural frequency present between the second and third common frequencies.

It is noted that these common frequencies are unique to this unconstrained boundary condition. For the implementation of SHM based upon frequency response in a system such as an aircraft, where the structure is fully constrained, it is not certain that the damage, similar to that detected in this study, would be detected at all. Another consideration is the method of measuring vibration velocity; clearly a highly sensitive laser vibrometer that measures hundreds of individual points is not practical.

With all these factors considered, it is determined that vibration monitoring, using the shifts in natural frequency, is an effective way of detecting damage such as disbonds in CFRP panels. It is clear that further studies are required to determine the limits to the use of this method of damage detection.

VI. Recommendations

It is recommended that further research be conducted to narrow down the limits of this method. This project was performed with a small sample size due to the extensive time required to fabricate each panel. Because of the small number of samples it is not certain whether the shift in frequencies in the panel with the smallest disbond are due to the disbond or to changes in other mechanical properties as a result of minor differences in material or processes. Therefore, the first area of further research is to fabricate more undamaged stiffened panels as well as panels with artificial disbonds of various sizes under the middle stiffener. This will minimise the uncertainty in the results and will determine the minimum size of the disbond that can be detected.

Along the same area of investigation is the location of the artificial disbond. The ETFE patches in this study were positioned centrally under the middle stiffener. Other locations for the patch to be inserted and tested for include: off centre under the middle stiffener, centrally under the side stiffeners, and off centre under the side stiffeners. The data from the analysis of these experiments could be used to determine if these disbonds are also
detectable and to what minimum size, as well as if the actual position of the damage can be determined from the shifts between different common natural frequencies.

Another area of interest would be to alter the boundary conditions of the test samples. The current testing was performed by suspending the test piece from its upper corners to simulate a free boundary condition. By testing with one or more edges constrained a wider range of analysis could be performed on the effectiveness of this form of vibration analysis.

Lastly, fabricating stiffened panels with different dimensions, number of plies, ply orientations and number of stiffeners would provide a valuable source of information from the subsequent testing and analysis.

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References