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Use of PVDF Strain Sensors for Health Monitoring of Bonded Composite Patches

Roger Vodicka and Steve C. Galea

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Airframes and Engines Division
Aeronautical and Maritime Research Laboratory

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ABSTRACT

The use of PVDF (polyvinyldiene fluoride) piezoelectric polymer material as a strain sensor for the detection of damage in bonded composite patches is investigated in this report. These sensors offer the advantage of requiring no power to function and the sensors may be manufactured to suit any size and geometry. PVDF sensors were bonded to a specimen representative of the F-111 wing pivot fitting doubler and tested under hot/wet conditions for a series of load cases. The output of the PVDF sensors was found to vary linearly with applied load but a dependence on loading frequency was observed. Damage growth within the specimen was detected by both strain gauges and PVDF sensors. Identical trends in damage growth were observed by both sensors. The environmental durability of the PVDF sensors was found to be very good, although care needed to be taken whilst handling the sensors to avoid physically damaging them.

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Executive Summary

For economic reasons there is a current trend to operate military aircraft well past their original design life. However, this results in a rapidly increasing number of airframe structural defects and gives rise to the urgent need for cost-effective, efficient repair procedures. This situation is extremely relevant to the RAAF where many aircraft types, such as the F-111, P3C, Macchi and the F/A-18 will have exceeded their design life well before they can be replaced. The application of bonded composite patches to repair or reinforce defective metallic structures is becoming recognised as a very effective and versatile procedure for many types of problems.

The goal for very demanding repair applications is to incorporate sensors, actuators and electronics in repair systems - smart repair systems - to monitor and report on the health of the repair and the repaired structure, as well as to actuate in order to prevent damage or failure of the repaired structure. Current research in this area is mainly focused on developing on-line health monitoring techniques for safety-critical bonded repairs. This will allow the operator to move away from costly time-based maintenance procedures toward real-time health condition monitoring of the bonded repair and the repaired structure and will allow timely decisions on preventative and scheduled maintenance before failure of the repair or repaired structure.

Sensors used for the health monitoring of bonded patches need to be robust, resistant to the service environment, accurate and reliable. It is also desirable to have sensors which require low operating power levels especially when used with 'stand-alone' in-situ data acquisition instrumentation. One established health monitoring technique is to use electrical resistance strain gauges to monitor the amount of extension and/or compression (strain) in the patch. Reductions in the amount of strain that a patch sees during service can signify a reduction in the effectiveness of the patch. However these sensors do require a substantial amount of power to operate. An alternative is to use piezoelectric polymer sensors, such as PVDF (polyvinyldiene fluoride). These types of sensors produce a voltage, due to the piezoelectric effect, when stretched or compressed, and therefore require no power to operate.

This report details the use of PVDF sensors to measure the health of a bonded repair representative of the F-111 doubler under various loading conditions in a hot/wet environment. An excellent correlation was found between the conventional electrical resistance strain gauges and the PVDF sensors,

indicating the applicability of the PVDF sensors for patch health monitoring. By operating continuously and reliably in extreme hot/wet environments these sensors exhibited excellent durability. However, further work is required to improve sensor bonding techniques and improve sensor robustness in order to reduce the risk of physical damage.

Authors

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Roger Vodicka graduated BSc. (Hons.) from Monash University and joined AMRL in 1990. He currently works in the area of composite materials and crack-patching repair technology. Current working projects include moisture diffusion properties of epoxies, battle damage repair, environmental certification of composite materials and composite manufacturing methods.

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Dr Galea graduated in 1980 with a Bachelor of Engineering (Mech) from the University of Queensland with first class honours and in 1983, he received a Masters of Engineering Science. He commenced employment with the Aeronautical Research Laboratory in 1983. In 1985 he commenced studies at the Institute of Sound and Vibration Research, University of Southampton, UK and received his Doctor of Philosophy from the University of Southampton in 1989. Dr Galea was appointed a Research Scientist in 1990 and Senior Research Scientist in 1992. Since 1990 Dr Galea has been working in the areas of composite structures, computational and experimental mechanics. He is currently managing tasks related to repairing aircraft structures with acoustic fatigue cracking and smart repair systems for aircraft structures, at the Aeronautical and Maritime Research Laboratory.

Contents

1. Introduction

For economic reasons there is a current trend to operate both military and commercial aircraft well past their original design life. This situation is extremely relevant to the RAAF where many aircraft types, such as the F-111, P3C, Macchi will have exceeded their design life well before they can be replaced. However, this results in a rapidly increasing number of airframe corrosion and cracking problems and gives rise to the urgent need for cost-effective, efficient repair procedures. The application of bonded composite patches to repair or reinforce defective metallic structures is becoming recognised as a very effective, cost-effective and versatile procedure for many types of problems. Immediate applications of bonded patches are in the fields of repair of cracking, localised reinforcement after removal of corrosion damage and for reduction of fatigue strain. The goal for very demanding repair applications is to incorporate sensors, actuators and electronics in repair systems - smart repair systems - to monitor and report on the health of the repair and the repaired structure, as well as to actuate in order to prevent damage or failure of the repaired structure. The F-111 boron/epoxy wing-pivot fitting reinforcement would have greatly benefited from such an approach. Current research in this area is mainly focusing on the assessment of new sensors which may be incorporated in bonded repair systems in order to achieve in-situ real-time measurement of patch integrity and effectiveness. This application would allow the operator to move away from current costly time-based maintenance procedures toward real-time health condition monitoring of the bonded repair and the repaired structure. These systems would allow timely decisions on preventative and scheduled maintenance before failure of the repair or repaired structure.

This paper addresses the use of piezoelectric film or PVDF (polyvinyldiene fluoride) as a sensing device to detect and monitor damage in bonded composite patches. Previous work has addressed the use of PVDF sensors to detect and monitor damage in metallic and composite structures [1, 2]. Material degradation in the patch can be due to a variety of factors including debonding in the adhesive layer, delamination in the composite and cracking in the metallic substructure or impact damage in the composite patch. Unlike traditional "passive" techniques for damage detection, e.g., C-scanning, these sensors have the ability to reflect the interaction of the load, geometry, material, structure and damage. Therefore they constitute an "active" methodology for structural damage monitoring. The structural significance of damage changes depending on the nature of the load/stresses applied to the damaged component. These sensors have the advantage in that they are readily applied over large areas of the patch and associated repaired structure and, hence, when incorporated with an in-situ processor, are able to provide real time assessment of the integrity of the repair and associated structure. Techniques developed can be incorporated in the initial application of the repair or, because of the ease of applying the piezoelectric films, could be incorporated on aircraft in current service.

The use of PVDF sensors for monitoring strains in aircraft structures is attractive for a number of reasons. The sensors do not consume power and may be shaped and sized as required. The PVDF sensors consists of a polymer film of polyvinyldiene fluoride (PVDF or PVF_2) coated with an electrically conductive layer such as silver. These devices generate a charge in response to mechanical stimulus or alternatively provide a mechanical strain when an electric field is applied across them. The voltage generated by the sensor is collected by the conductive coating on both sides of the film. These materials exhibit excellent mechanical strength, low acoustic impedance and possess a flat response over a wide frequency range as well as a broad dynamic response. Due to their low mechanical impedance a number of piezoelectric films can be distributed along the structure without drastically affecting its mechanical properties. The polymer film itself is a close chemical analogue to teflon (PTFE) and should therefore have very good chemical and moisture resistant properties. The films are also rated for use up to temperatures of 80°C. Above this temperature the polymer morphology of the film changes and the piezoelectric effect, induced by polymer crystallinity, ceases. Co-polymers of PVDF are available which extend the temperature range of the sensor up to 120°C.

If the sensor is bonded to the structure then the sensor output is proportional to changes in surface displacement. Hence this device can be used to detect variations in structural and material properties, e.g., material compliance. This investigation elaborates on the use of piezoelectric films to detect and monitor damage in composite structures by observing changes in surface displacement. The films are not isotropic and the strain response differs in the 1 and 2 directions (i.e. they are orthotropic in nature where the draw direction of the polymer film, direction 1, has the greatest sensitivity). Films should be aligned as to give the greatest sensitivity.

The sensors themselves are relatively easy to construct and may be cut with a sharp pair of scissors. The silver coating may be removed from the film as required using a strong solvent such as MEK (methyl-ethyl-ketone). The integrity of the silver coating is of utmost importance as it conducts the voltage. Flexing of the coating or mechanical abrasion may damage the coating rendering the sensor useless. The films are easily torn if a sharp cut is present to initiate the rip.

This paper describes an experimental investigation into the use of PVDF sensors to detect and monitor damage in bonded composite patches. PVDF sensors and strain gauges are used to detect and monitor damage in an F-111 doubler representative specimen. The application to in-service aviation environments is also examined, in particular the performance of the sensors under hot/wet conditions coupled with mechanical spectrum loading. Also the general robustness of the sensor is examined. The specific objectives of the program of work are to assess:

1. The suitability and effectiveness of PVDF piezoelectric films, as substitutes for strain gauges, for in-flight health monitoring of composite repairs and doublers
2. The environmental resistance of such sensors operating under hot/wet environmental conditions.

2. Experimental Setup and Procedure

2.1 Specimen Test Configuration and Setup

The F-111 bonded doubler representative specimen consisted of a 3.4 mm thick aluminium specimen with tapered 29 ply unidirectional boron/epoxy doublers bonded to each side to retain symmetry (Figure 1). The doublers were bonded to the aluminium substrate using FM73 epoxy structural adhesive. The boron doublers are tapered at the ends with a taper, or step-up, rate of 1 ply every 3 mm. These specimens are based on the representative dog-bone specimens described in [3]. The specimen was enclosed within anti-buckling guides to avoid lateral bending during compression loading. Hydraulic grips were used to grip the specimen and tests were performed in an INSTRON hydraulic testing machine.

The entire specimen was enclosed in a shroud of polyethylene plastic which had inlets and outlets for hot air fed by a fan-forced oven. An inlet was also included to introduce steam from an urn. The setup produced an atmosphere of around 50°C ±2°C and 50% ±5% R.H. for the duration of the load cases.

2.2 Sensor fabrication and attachment procedure

PVDF film produced by ATOCHEM was used. The films, coated with a conductive silver ink are readily etched with a cotton bud soaked in MEK solvent and cut to size with an ordinary scalpel. Figure 2 shows a simple sensor design, suitable for bonding to a component. Plastic cable "clinches" which use contacts that crimp on to the PVDF film were used to connect to the upper and lower parts of the sensor. The clinches were then connected to wire leads. To ensure good contact between the clinches and the conductive silver ink a layer of conductive epoxy (Circuit Works Conductive Epoxy, RS Components, U.S.A) was used. The clinches are then squeezed and crimped on to the film providing a solid electrical and mechanical contact.

The PVDF sensors were bonded to the boron epoxy doubler at 8 locations using '5 minute Araldite' epoxy adhesive. To ensure high temperature properties the adhesive was post-cured at 60°C for 16 hours. The adhesive has a T_g of around 60°C when post-cured. The entire sensing area of the PVDF was coated in Araldite adhesive to protect the film from the environment. Care was taken to correctly align the draw direction of the polymer film with the loading direction (ie, to align the highly sensitive direction of sensor in the direction of maximum strain).

Four strain gauges (KYOWA KFG-2-120-C1-11L3M3R) were also applied to the doubler. Strain gauge and PVDF sensor positions are shown in Figure 1. Strain gauges are identified by the designation A1, A4 and B1, B4. Strain gauges A1 and B1 are located on the first ply (step) on each of the boron doublers. Strain gauges A4 and B4 are on the fourth ply (step) on the doublers. Strain gauges were bonded using MBOND 200 cyanoacrylate adhesive. Results from the strain gauges are used for comparison to the output of the PVDF sensors and will allow an evaluation of the PVDF sensor's effectiveness in detecting damage in the doubler repair during load cycling.

Dimensions of the PVDF sensors are given in Table 1. Note that sensors 2, 4, 5 and 6 cover the first 3 plies (steps) of the tapered region of the boron doubler while the strain gauges A1 and B1 cover only the first ply. The four strain gauges A1, B1 and A4, B4 each have a sensing length of 2 mm.

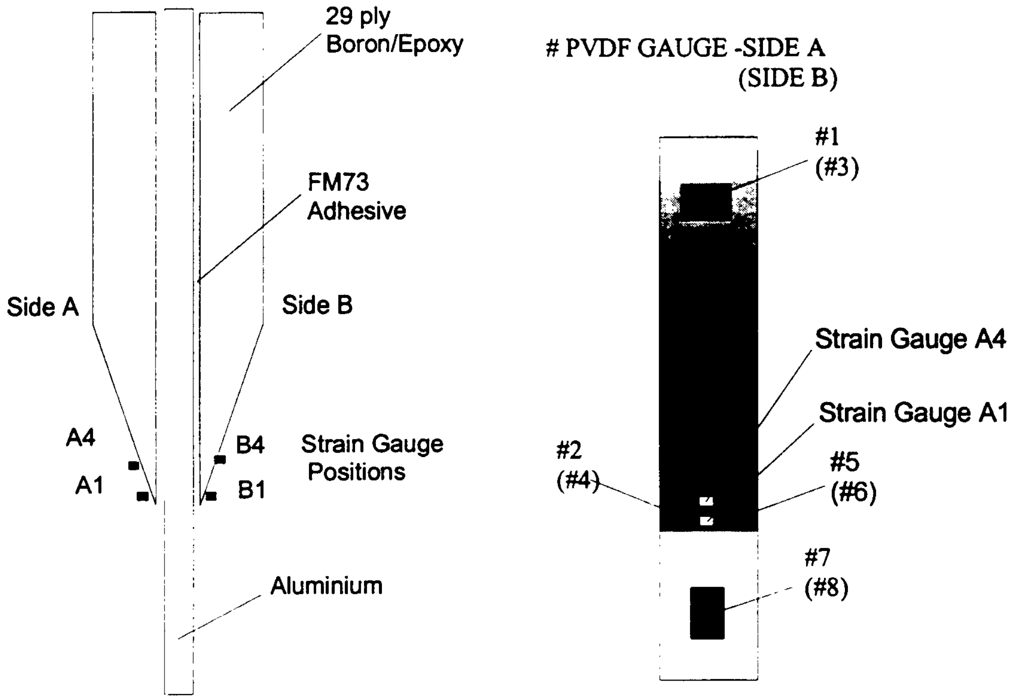

Figure 1: Schematics (side-view left, top-view right) of the F-111 doubler specimen, with the location of PVDF sensors and strain gauges indicated.

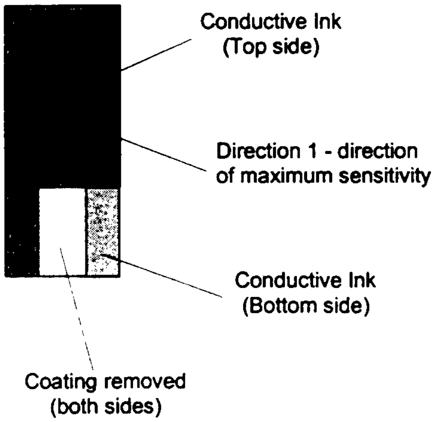

Figure 2: Schematic of PVDF sensor (dimensions about 20 mm long by 10 mm wide).

Table 1: Dimensions of PVDF sensors.

Sensor #	Sensor Location	Length (along loading direction), in mm	Width (perpendicular to loading direction), in mm
1	Far-field Boron	13	18
2	Side A Boron first 3 steps	8	8
3	Far-field Boron	13	18
4	Side A Boron first 3 steps	7	7
5	Side B Boron first 3 steps	8	9
6	Side B Boron first 3 steps	7	6
7	Far-field Aluminium	18	10

2.3 Load Cases

All load cases, described below, were carried out under hot/wet conditions (50°C and 50% R.H.). The total number of hours the specimen was exposed to hot/wet conditions and cyclically loaded is in excess of 250 hours.

2.3.1 Constant Amplitude Loading

The frequency and amplitude response of the sensors was initially assessed by loading the specimen with a variety of sinusoidal waveforms. In theory there should be no frequency dependence with PVDF sensors. In this investigation the frequency response of the PVDF sensor coupled to the data-acquisition system used was unknown and had to be tested. Constant amplitude sine wave loading was applied to the specimen at frequencies of 0.5 Hz and 3 Hz and at loading levels of ± 2 kN, ±5 kN and ±13.29 kN.

2.3.2 Spectrum Loading

The ability of the PVDF sensors to detect damage in the boron/epoxy doubler is to be examined by comparing the outputs of strain gauges to those of the PVDF sensors.

One block of F-111 spectrum loading is equal to 18137 load cycles, or about 500 hours of typical aircraft use. Sixty blocks of the spectra were used to represent 20 years of use (one lifetime) with a factor of five confidence. The spectrum is applied at 3 Hz at loads representative of F-111 in-service flight loads. The maximum loads applied in the spectrum were +8 kN in tension and -20 kN in compression. The entire fatigue loading case consisted of:

1. F-111 spectrum loading for 60 blocks.
2. Sinusoidal cycling at 3 Hz for 100,000 cycles between loads of +3.3 kN to -10 kN.
3. Sinusoidal cycling at 3 Hz for 18,000 cycles between loads of +4.35 kN and -15 kN.

4. Sinusoidal cycling at 3 Hz for 8849 cycles between loads of +6.58 kN and -20kN.
5. F-111 spectrum loading for a further 60 blocks.

2.4 Data Acquisition

Data was acquired from all eight PVDF sensors, four strain gauges and a load channel using a PC equipped with an Advantech PCL812 data acquisition card. The card was set for +/- 10V inputs. At a resolution of 12 bits this gives a bit-error of about 5mV. PVDF output was fed directly to the analog input channels through a screw terminal board with no conditioning or filtering.

Note that no form of amplification or signal conditioning was used during data sampling. The use of charge amplifiers is common practice in many applications of PVDF sensors, but these are not used here in order to demonstrate the simplicity of the sensor system and to show that power requirements to log sensor data are confined to running a data acquisition system only. The shortfall of this approach is that there may be a frequency dependence of the PVDF output. This is not an issue in this test programme as the loading spectrum is performed at constant frequency and the output may be calibrated against a series of load levels. Furthermore, in order to detect damage growth it is the ratio of sensor outputs not the true values which are important.

Temperature and humidity was monitored throughout the test using a VAISALA temperature and humidity probe placed in close proximity to the specimen. Temperature and humidity data was not acquired by the data acquisition system but was monitored throughout the test to ensure correct conditioning environment. A thermocouple was also placed on the specimen to control the heating of the specimen from the fan-forced oven.

2.4.1 Constant Amplitude Loading

Sensor output data was acquired at rates between 150 Hz to 200 Hz. This was done in order to sample enough points on each sine-wave cycle to ensure accurate measurement of amplitudes and to ensure that enough points were available to digitally filter any noise in the signal effectively. DASYLAB software was used to drive the data acquisition card and save the data to the PC.

2.4.2 F-111 Spectrum Loading

Application of 60 blocks of F-111 spectrum cycling represents about 15 days of testing at eight hours per day. The outputs from both the strain gauges and PVDF sensors were monitored during testing. Data was acquired for 15 seconds every 15 minutes at a frequency of 150 Hz.

2.5 Data Analysis

The data was analysed using Microcal ORIGIN software. The PVDF output waveforms produced significant voltages for the load cases given (> 5 V) but exhibited some noise around 50 Hz. This was filtered using a Fast Fourier Transform (FFT) filter with a low-pass cut-off of around 30 Hz. This noise was not present on the load signal or the four strain-gauge signals.

Figure 3 shows an example of PVDF data acquired and the application of the FFT smoothing algorithm. Peak-to-peak sensor output amplitudes were reduced from the FFT filtered data using a peak-finding algorithm.

3. Results

3.1 PVDF sensor failures

Out of the eight PVDF sensors which were used initially only four survived all the load cases and conditioning. The most common cause of gauge failure was due to physical handling. The PVDF material is susceptible to tearing. Sensor #8 was damaged during application to the specimen. Sensors #2 and #6 were torn while the specimen was placed within the anti-buckling guides. Sensor #1 failed due to the electrical contact clinch falling off.

Sensors also failed to give correct output if condensing humidity covered the sensor wires and clinches. Any exposed electrical contacts need to be thoroughly insulated from moisture during hot/wet testing.

3.2 Frequency and Amplitude dependence

The output of the PVDF sensors was found to be dependent on the applied cycling frequency. The response to sine waves of 3 Hz and 0.5 Hz was examined. Figure 4 shows the frequency and amplitude dependence of a given PVDF sensor. The output varied linearly with load amplitude for all sensors, with higher frequencies producing the greater output. This frequency dependence is due to the data-acquisition instrumentation used. The mismatch in impedance between the data-acquisition system and the PVDF sensor introduces this effect. The use of charge amplifiers provides a solution to this but introduces greater complexity. The loads described here are -20 kN and +6.58 kN. The peak-to-peak strain measured at the first ply step of the doubler was in excess of 2000 $\mu\varepsilon$ at these load levels.

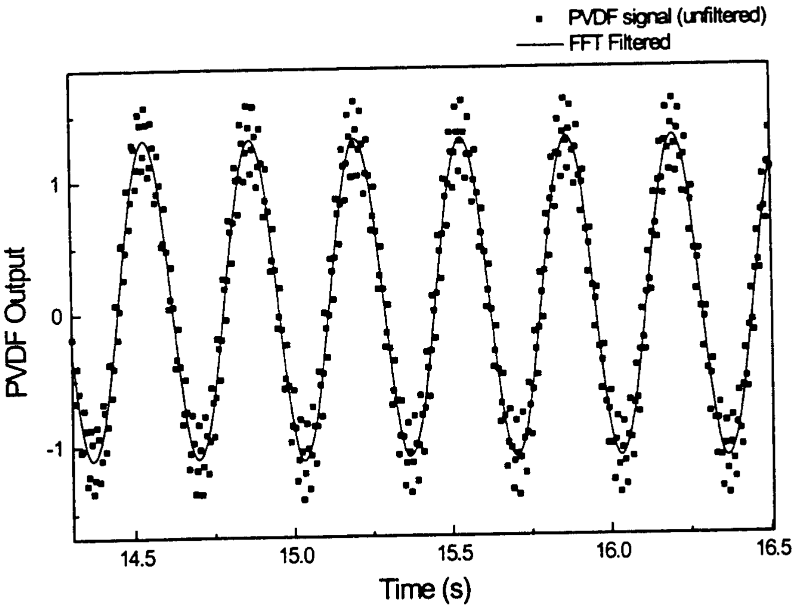

Figure 3: FFT Filter applied to PVDF signal values.

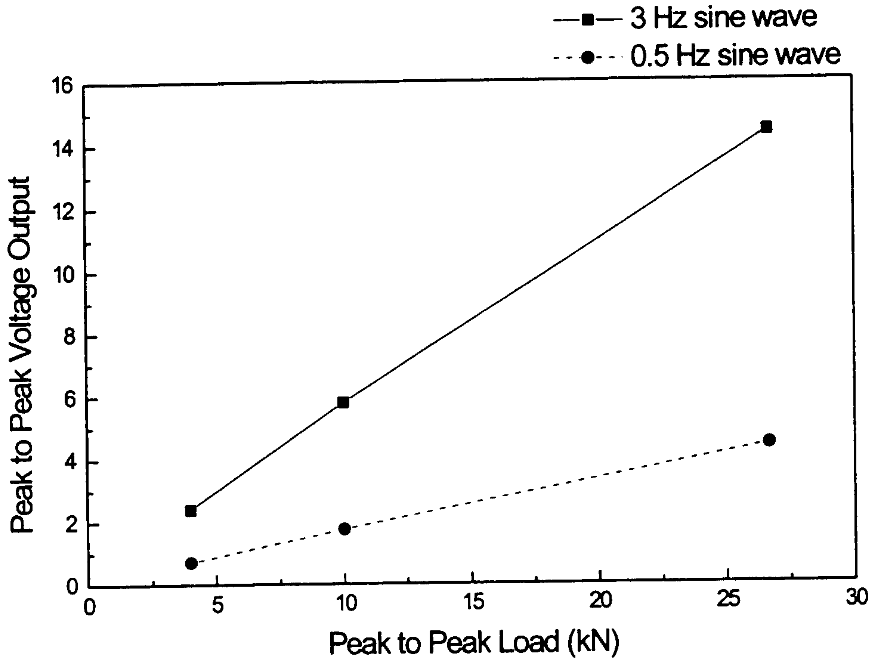

Figure 4: Loading amplitude and frequency dependence of PVDF output for sinusoidal loading. Voltage output is a peak-to-peak value

3.3 Load Cases

The first three load cases listed in section 2.3.2 showed no changes in strain gauge or PVDF output signal indicating that the specimen did not see any damage. The fourth load case, cycling between F-111 spectrum limit loads, induced damage in the specimen as witnessed by both strain gauges and PVDF outputs. Further damage was induced in the specimen when a further 60 blocks of F-111 spectrum was applied.

3.3.1 Constant Amplitude Load Cycling

The detection of damage in the doubler specimen was made by examining the output levels of the PVDF sensors as well as the response of the strain gauges. Initial signs of damage were detected from the PVDF sensor output using the graphical display in the DASYLAB data acquisition software. The output of PVDF sensor #5 was seen to steadily decrease over the 8849 cycles made between load limits of - 20kN and +6.58kN at 3 Hz. A plot of the data, i.e. PVDF peak-to-peak voltage, at this sensor location is shown in Figure 5. This figure shows a reduction of about 0.8V over the entire load case. This represents a 6% loss of signal compared to the initial value. A decrease of 260με was measured at strain gauge B1 over the load case. At these load limits the initial peak to peak strain output is 2330με. This decrease therefore represents a 11% decrease in strain at this location. Figure 6 shows the change in strain at strain gauge location B1 with number of applied load cycles. No other gauges showed decreases in output during this loading case.

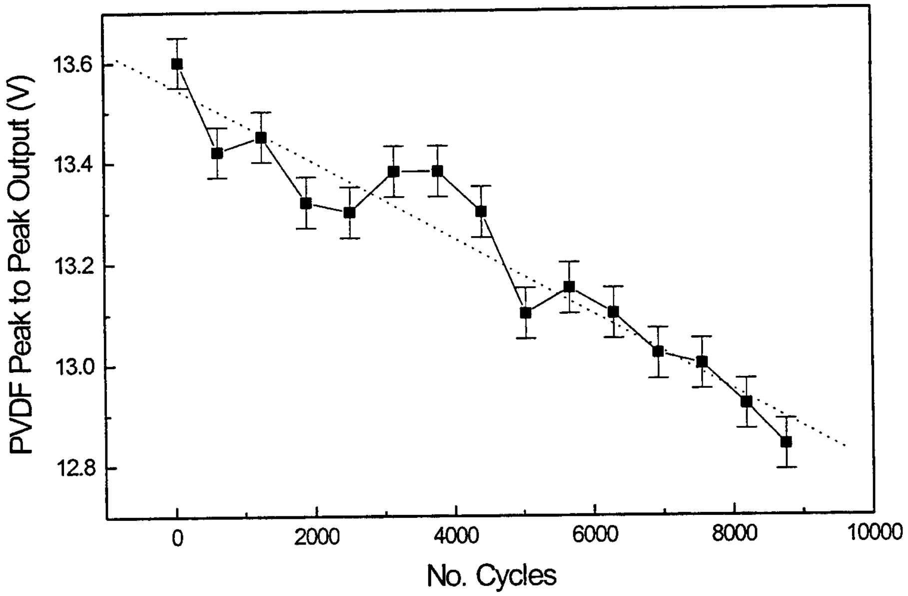

Figure 5: Reduction in PVDF sensor output (#5) with increasing number of applied constant amplitude loading cycles, indicating damage and damage growth in the specimen.

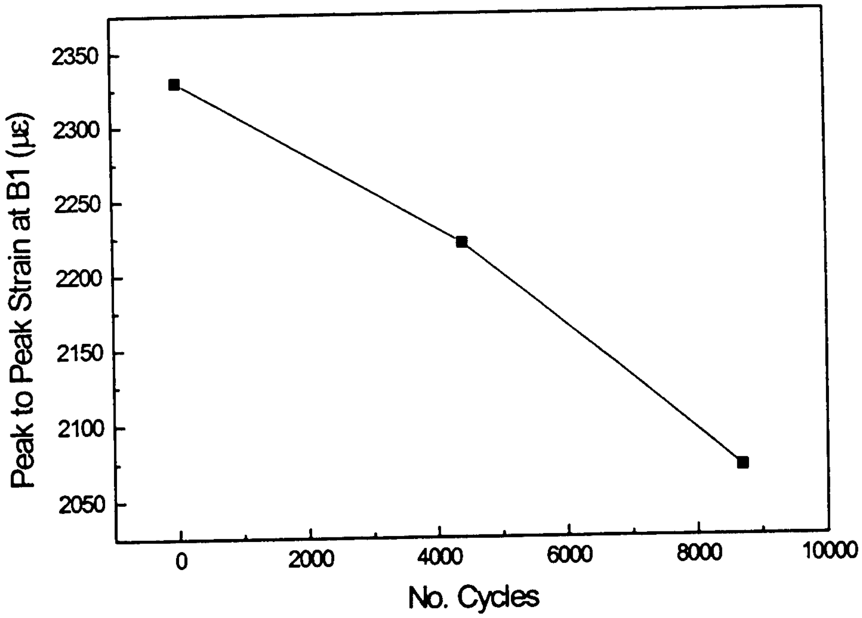

Figure 6: Reduction in strain gauge B1 peak-to-peak strain, with increasing number of applied constant amplitude loading cycles, indicating damage growth in the specimen.

3.3.2 F-111 Spectrum Loading

After damage was detected in the specimen during constant amplitude sinusoidal loading it was decided to switch back to the F-111 spectrum and examine if further damage growth would occur. Application of a further 60 blocks of F-111 spectrum cycling was undertaken.

Damage growth was observed during F-111 spectrum loading at PVDF sensor #5 only. A comparison was the made between PVDF sensor #5 and PVDF sensor #4 in order to produce a damage indicator which is basically a ratio of the signal at the damaged location (PVDF sensor #5) to a signal at an undamaged location (PVDF sensor #4). Comparison was then made between PVDF sensors #5/#4 and strain gauges A1/B1. This data was normalised with respect to unity representing the initial damage indicator ratio, and is plotted in Figure 7. A good correlation exists between the strain gauge and PVDF data.

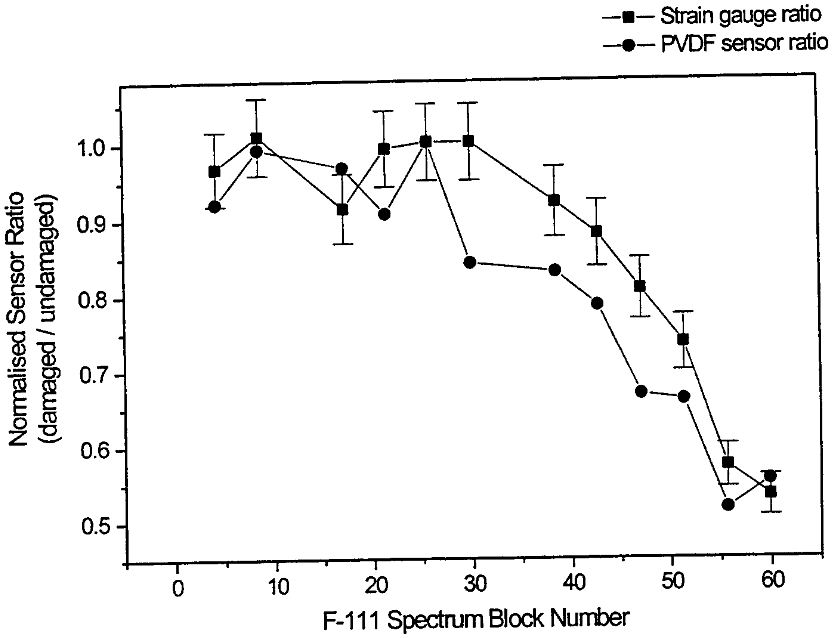

Figure 7: Variation of strain gauge and PVDF sensor output ratios (damaged/undamaged) with increasing number of applied F-111 spectrum blocks. Data is normalised with unity representing the undamaged state.

The exact nature of the damage is not examined here but rather the suitability of the PVDF sensors to the task of faithfully reproducing the results of conventional strain gauges for health monitoring.

During the data analysis it was noticed that a slight phase-lag occurred between some of the PVDF sensors. Figure 8 illustrates this phase-lag for an input sine-wave loading at 3 Hz. A lag of about 0.02 seconds is noted. The sampling rate for the test was 200 Hz, ie: a data point every 0.005 seconds. This lag was not observed in the strain gauge data. The cause is likely to be due to impedance mismatch between the data-acquisition system and the PVDF sensor. Such effects are unlikely to be encountered by including high impedance devices such as charge amplifiers to the instrumentation.

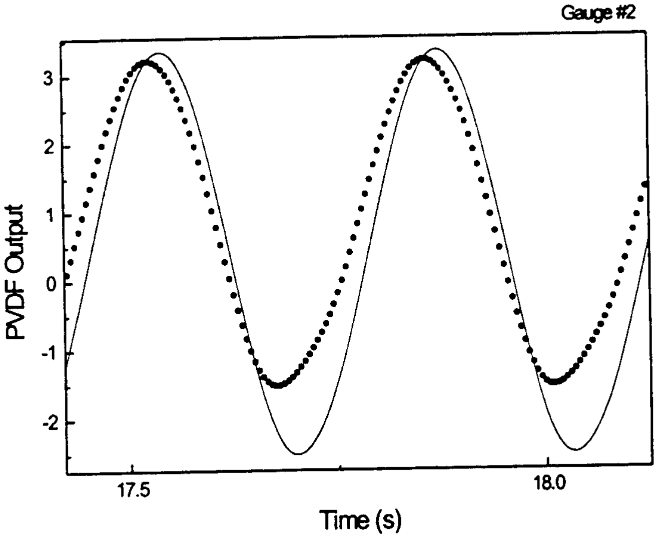

Figure 8: Phase lag seen between two PVDF sensors on different parts of the specimen.

4. Discussion

The PVDF sensors seem well suited to the task of strain and health monitoring on structures. Although a direct comparison of strain gauge values and PVDF output cannot be made the trends in results between the two are clearly seen. This is especially obvious when comparing Figures 5 and 6 which show the growth of damage in the doubler when cycling between spectrum limits. Lower levels of signal loss with increasing damage are seen by the PVDF sensors. This is due to the fact that the sensing area of the PVDF is of the order of 10 mm by 10 mm whereas the strain gauge covers a much smaller region (with about 2 mm sensing length). The use of PVDF sensors with smaller areas covering the critical regions more closely would give an even better response to any damage growth.

Excellent correlation between the strain gauge and the PVDF sensor is achieved when the normalised ratio of strain at the critical region of the patch to the strain in the far-field is used (as shown in Figure 7). This ratio or 'damage indicator' appears to be sensor independent. A normalised sensor ratio value of unity indicates good health (ie: no damage) and a value approaching zero indicates substantial damage.

Noise suppression in the laboratory environment is important. It may be necessary to filter the PVDF signal using a low-pass filter. This is a good solution for low frequency cycling but may interfere with outputs from high frequency load inputs.

The sensitivity of the PVDF sensors appears to be adequate, with high voltage output levels recorded for the type of strains encountered in critical areas on an aircraft such as in the F-111 doubler. The output recorded with this system showed a frequency dependence due to the impedance mismatch between the data-acquisition system and the PVDF sensor. Such effects would be significantly reduced by incorporating high-impedance charge amplifiers in the instrumentation [2]. Although the frequency effect may appear to limit the usefulness of the sensor, since elaborate strain readings will be frequency independent, the sensor is still suitable for health monitoring since it is the ratio of the outputs which is important. That is, the necessity for additional complex instrumentation such as charge amplifiers is eliminated if relative measurements are used as the health monitoring technique.

The PVDF sensors performed well in the hot/wet environment. In some instances condensing moisture caused temporary electrical shorts. This would be easily overcome in the future by using a moisture resistant resin (eg, epoxy) on all exposed electrical contacts. The area of the join between the clinch and the PVDF sensor is particularly critical. This area needs to be sealed in epoxy with the electrical joins supplemented with conducting epoxy.

Some of the larger PVDF sensors, notably #3 and #7, suffered some disbonding from the specimen. Smaller PVDF sensors, #4 and #5, did not suffer from this. Also in some cases the silver ink coating disbonded from the PVDF polymer. It appears that the disbonding of the PVDF sensors may be a surface treatment problem or it could be related to the poor bond between the PVDF material and the silver ink coating. Care is required in ensuring that a good bond between PVDF sensor and material is formed. A good way to do this may be to cure a layer of epoxy over the entire sensor surface and then secondarily bond it to the material after an appropriate surface treatment. This technique may reduce the possibility of incorrect coating of the PVDF sensor. Bonding problems such as these may be overcome using epoxy resins used for strain gauging for hot/wet environments.

The manual handling of the PVDF sensors is critical. The PVDF sensors need to be well protected from any mechanical damage if they are to be used successfully in the field. This may necessitate the use of a cover over the sensor. The need to use anti-buckling guides on this specimen made it particularly difficult to place the PVDF sensors. This test type represents an extreme case of PVDF sensor placement and manual handling problems. Placing sensors on flat surfaces with no interference would be much easier in comparison.

Further studies may concentrate on using PVDF sensors within adhesive bondlines to measure peel stresses in the adhesive as shown by the work of Anderson et al [4].

5. Conclusions

PVDF piezoelectric sensors are a good alternative to conventional strain gauges and are suitable for use in hot/wet environments up to at least 50°C when bonded using conventional epoxy adhesives and a suitable surface treatment. It is however important to protect all electrically conducting parts of the sensor and connecting hardware against condensing humidity. Data from PVDF sensors were acquired using inexpensive off-the-shelf equipment. Both the strain gauges and the PVDF sensors were able to monitor the growth of damage within a specimen representative of the F-111 doubler.

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7. Acknowledgments

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DISTRIBUTION LIST

Use of PVDF Strain Sensors for Health Monitoring of Bonded Composite Patches

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19. ABSTRACT

The use of PVDF (polyvinyldiene fluoride) piezoelectric polymer material as a strain sensor for the detection of damage in bonded composite patches is investigated in this report. These sensors offer the advantage of requiring no power to function and the sensors may be manufactured to suit any size and geometry. PVDF sensors were bonded to a specimen representative of the F-111 wing pivot fitting doubler and tested under hot/wet conditions for a series of load cases. The output of the PVDF sensors was found to vary linearly with applied load but a dependence on loading frequency was observed. Damage growth within the specimen was detected by both strain gauges and PVDF sensors. Identical trends in damage growth were observed by both sensors. The environmental durability of the PVDF sensors was found to be very good, although care needed to be taken whilst handling the sensors to avoid physically damaging them.