Surface strain distribution method for delamination detection using piezoelectric actuators and sensors

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Abstract. This paper presents an experimental study into detection of delamination in composite beams by using surface strain distribution method. Two piezoelectric (PZT) patches were surfaced bonded to each composite beam; one was used as actuator to excite the beam structure whereas the other was custom-designed and used as sensor. The custom-fabricated PZT sensor has 15 evenly-distributed electrode strips which enable measurement of 15 surface strain readings in the form of electric charge output. The effects of various parameters, e.g., vibration modes, excitation frequency and sensor debonding, on damage detection sensitivity were investigated. It is shown that the variation in sensor charge output distribution can be an effective indicator of the presence, size and location of localized delamination in composite beam and debonding between a sensor and its host beam.

1. Introduction
Owing to their high specific stiffness and strength, laminated composites materials have been widely used in aerospace industry, for example, Airbus 380 and Boeing 787 airframes uses 25% and 50% by weight composite materials, respectively. However, composite laminates are prone to delamination damage which can be caused during manufacturing or in service. The presence of delamination can degrade severely key mechanical properties of composite laminates, and has the potential of compromising structural integrity. Thus development of an early damage detection method for delamination is one of the most important technologies in maintaining the integrity and safety of composite structures. The need of nondestructive techniques for structural health monitoring or diagnosis has led to continuous development of damage detection methods using structural dynamic characteristics. The basic premise of such methods is that any localized damage in a structure changes its stiffness, damping and mass, which in turn alters its dynamic responses, such as natural frequencies and vibration modes, wave propagation etc. Many researchers used one or more of the above characteristics to detect and locate delamination in a composite structure [1-3]. It was shown in the literature review [3] that that natural frequencies are not sensitive to small damages, and modal shapes are difficult to measure and not sensitive to the presence of damage; however, modal shape curvatures was shown to be very sensitive to damage and the effect can be highly localized in the damage region [4]. The use of curvature of a mode shape has also been considered by other authors [5-9]. Measurement of structural modal shape curvatures can be difficult. Compared to the curvature of a
modal shape, surface strain distribution for a modal shape has the similar characteristics and can be measured confidently using surface bonded sensor. It was pointed out that strain measured mode shape is more effective at identifying the damage location than displacement mode shapes for damage in a steel truss [5-6]. Therefore surface longitudinal strain distribution can be used as a damage indicator for evaluating and locating a structural damage.

The concept of using piezoelectric materials in the form of thin films as actuators and sensors mounted on to a structure was proposed for monitoring the health of heterogeneous structures [10]. The advantage of using active material for structural health monitoring is that the condition of the structure can be continuously monitored with the aid of an onboard microprocessor and thus the sensor output can be continuously evaluated. Many studies in this field have focused on experimental investigation of the changes in the recorded output data of piezoelectric sensors due to damages and explored the possibility of damage detection using PZT patches (e.g., [11-18]).

Based on our previous studies [15-18], this paper aims to extend and validate this strain distribution method for delamination detection. This study investigates experimentally the influences of different parameters, such as actuator, sensor and delamination location, the magnitude and frequency of the input actuator voltage etc, on damage detection. In addition, the effect of sensor edge debonding on damage detection is also investigated for the first time. Presented is a comparison of the normalized sensor charge output distributions for vibration modes 1 and 3 between the pristine and delaminated beams and/or beam with a debonded sensor, and between the predicted and measured results. Experimental validation of the damage detection of using sensor charge output (SCO) distribution particularly for vibration mode 3 is also presented. It is shown that the custom-designed sensor and the surface strain distribution method are effective in identifying the presence, location and size of a delamination.

2. Delamination detection algorithm

Figure 1 shows a schematic of a composite cantilever beam with an embedded delamination parallel to the beam surfaces. The beam is bonded with two piezoelectric patches, one is used as actuator excited by a sinusoidal voltage input, and the other is used as sensor with striped-electrode pattern mounted on the top surface of the beam segment beneath which a delamination is embedded.

![Diagram of a composite beam with delamination](image)

Figure 1. Schematic of a clamped composite smart beam with delamination

The custom-fabricated PZT sensor is shown in figure 2. The lower surface of the sensor is fully metalized whereas its upper surface is metalized with a pattern of electrode strips separated by uniform gaps, namely gridding electrodes. The electrode strips can be coated by depositing conductive metal or following similar procedure for manufacturing integrated or printed circuit board. It is well known that sensor signal can only be output through the electrodes, the required sensor charge output along its length can be evaluated by determining voltages of the evenly distributed electrode strips and the capacitance of the piezoelectric layer. The direct piezoelectric equation is used to calculate the output charge induced by axial strains. Since no external field is applied to the sensor layer, the electric field displacement developed on the sensor surface is directly proportional to the axial strain acting on the sensor. If the PZT is poled along the thickness direction of the sensor with...
the electrodes on its upper and lower surfaces, the output voltage \( V_s \) measured from an electrode strip, which locates between \( x_0 \) and \( x_1 \), is thus given by [15]

\[
V_s = \frac{t \cdot b \cdot e_{31}}{\xi A_s} \int_{x_0}^{x_1} (\varepsilon_x) dx = \frac{t}{\xi A_s} Q_s
\]

where \( A_s \) is the area of the electrode, for a rectangular electrode strip, \( A_s = b_s t_s \), \( b_s \) and \( t_s \) are the width and thickness of the electrode strip respectively; \( \xi \) is a dielectric constant; \( e_{31} \) is the piezoelectric strain constant, and \( Q_s \) is the sensor charge.

### Figure 2.
A schematic of the custom-built sensor with distributed electrode strips

Since sensor charge output is proportional to the surface strain of the beam, the ratio of sensor charge output measured at two different points along the beam is constant. To tell the difference of sensor charge output between a pristine beam and a damaged beam more effectively, also to effectively analyze the influence of major parameters on the sensitivity of damage detection, we introduce and compare the non-dimensional sensor charge output (NSCO) and non-dimensional sensor charge output difference (NSCOD). For example, considering the influence of strip edge, NSCO and NSCOD can be defined by

\[
NSCO = \frac{SCO}{SCO \text{ at the second strip}}
\]

\[
NSCOD = \text{ABS}(NSCO \text{ of pristine beam} – NSCO \text{ of damaged beam})
\]

### 3. Experimental

3.1. Specimen preparation

Three laminated beams, referred to as specimen A, B and C, of 25mm wide and 1.44mm thick were fabricated using 8-ply T300/F593 plain weave composite prepregs as shown in figure 3. Teflon films were used to form single embedded delamination of 40 mm long on the midplane of the laminated beam in specimen A and B. Specimen C is a pristine one. The dimensions of TRS610 PZT actuator are 30mm long, 25mm wide and 0.4 mm thick. The TRS610 PZT sensor is 60mm long, 25 mm wide and repetitive electrode pattern is 3mm long and 25 mm wide electrode strips separated by 1 mm gaps. When a beam specimen is clamped as shown in figure 1, the entire beam length was 0.58m, and the distance of left end of the actuator, sensor and delamination from the clamped end was 0.18m, 0.25m and 0.26m, respectively, except for specimen A the distance of the actuator was 0.1m. For specimen B, an edge debonding of 12mm long was introduced at the left end of the PZT sensor.

3.2. Test setup and procedure

The composite beams were clamped at one end and free at the other as shown in figure 4. Figure 5 depicts the block diagram illustrating how the experiment system works. The testing set up consists of the following electronic equipments: (a) NI SCXI-1327 signal conditioner with 8 channels but only 6
used, PI E-500 HVPZT Amplifier (3 channels, providing up to 500volts), PI E-500K012 LVPZT Amplifier (6 channels), Data acquisition board (DAQ) for actuation and sensor data acquisition, and PC with a data acquisition system and LabView software for virtual controller.

Lab-view files were created, one was used to evaluate the first three frequencies for the specimens, the other to generate loading for PZT actuator with a sinusoidal voltage \( V(t) = V_a \sin \omega t \). The testing procedure, including load application, data acquisition and processing, used for all three specimens was identical to ensure repeatability.

**Figure 3.** Photograph of three beam specimens bonded with PZT actuator and sensor: A with single delamination; B with delamination and sensor edge debonding; C perfect beam

**Figure 4.** Photographs of (a) the cantilever beam test setup and (b) the used electronic instruments
The sensor charge output was found to be sensitive to environmental noises, arising from air currents on the beams and local thermal fluctuations. The measured data in time domain were contaminated and could not be used directly to perform FFT to obtain the discrete output voltage data from electrode strips. To minimize the influence of random noise, average signal was used. In addition, inadvertent DC bias may be accumulated in the output signal due to repetitive tests, and to remove this effect, we computed the mean of the measured waveform samples and then subtracted it from each sample before performing FFT. For achieving enhanced frequency domain resolution, two different sample rate were used, namely, 16ms sample rate for mode 1 and 20ms sample rate for mode 3. A total of around 4000 data points (60 seconds) were recorded for each vibration response. Only modes 1 and 3 were measured.

We modified the method of recording the sensor signal previously used [15-17] by reading sensor signal of multiple continuous points in one test rather than one point only in one test. Because only 6 channels of the sensor signal conditioner were available, three sets of tests were required to completely measure one sensor charge output distribution for each specimen corresponding to one vibration mode, and each set of test was repeated 10 times in order to obtain average signal. Namely, the first 10 tests record the SCO signal from electrode strips 1-6; the second 10 tests record readings from strips 5-10; and the third 10 tests record data from electrode strips 10-15. After performing the FFT, three sets of data for one vibration mode of one specimen were obtained. These three sets of data were then curve fitted in least square regression sense. Figure 6 depicts the case for mode 1 of specimen A.

Finally, the three sets of data were joined together based on the common data points (for example, data sets 1 and 2 have common points of strip number 5, 6; data sets 2 and 3 have common point of...
strip number 10) to form a complete SCO distribution for this case. The constructed sensor charge output distributions are smoother and have enhanced repeatability compared to those obtained using previous sampling method [15-17].

3.3. Test results and discussion

Table 1 lists the average values and their standard deviations of the first three frequencies for all specimens measured repetitively 10 times. The first three frequencies of the specimens were measured by applying an impact load at the free end. It is evident that specimen A and B have natural frequencies lower than specimen C due to presence of delamination and debonding.

| Specimen      | Mode | Measured  |
|---------------|------|-----------|
| A             | 1    | 4.05 (±0.008) |
| (delamination + debonding at strips 12 and 13) | 2    | 21.52 (±0.019) |
|               | 3    | 64.91 (±0.18) |
| B             | 1    | 3.99 (±0.009) |
| (delamination + left edge debonding at strips 1 and 2) | 2    | 21.50 (±0.011) |
|               | 3    | 64.45 (±0.26) |
| C             | 1    | 4.12 (±0.008) |
| (perfect beam, no delamination, no debonding) | 2    | 23.58 (±0.017) |
|               | 3    | 65.70 (±0.31) |

Figure 7 depicts the measured sensor voltage output and its error bars versus the electrode strip number for mode 1 for specimen A, B and C, respectively. For all specimens, the actuation voltage applied was chosen to be 150 volts, and the actuation frequency used was 4.2 Hz for specimens A and C and 4.0 Hz for specimen B. It is evident that the standard deviation for each specimen is small, namely, 0.13 and 0.12 for specimen A and C, which indicates a good repeatability of the testing results. As shown in figure 7(a) for specimen A, there is a sudden drop in the sensor voltage reading at electrode strip number 12 and 13. This is due to the presence of debonding between the sensor and its host beam in the region of electrode strips 12 and 13 which occurred incidentally during sensor bonding. In figure 7(b), the sensor voltage output from strips 1 to 3 are almost zero due to presence of the sensor edge debonding of 12 mm long in this region. This observation clearly indicates the influence of sensor debonding in terms of setting sensor voltage output to zero or a close to zero constant for an edge or mid sensor debonding as the debonded sensor segment experiences zero or close to zero straining [19].

Figure 8 depicts the measured sensor voltage output and its error bars versus the electrode strip number for mode 3 for specimen C and B respectively. Similar to these for mode 1, the actuation voltage applied to the actuator was 150 volts, and the actuation frequency used was 66 and 65 Hz for specimens C and B, respectively. Compared to the results for mode 1 in figure 7, it is evident that the error bars in figure 8 are relatively large. This indicates that the test repeatability for mode 3 is not as good as for mode 1 because the high frequency and complex modal shape involved are prone to influence of environmental noises.

Figure 9 depicts the comparison of the measured NSCO and NSCOD results for vibration modes 1 and 3 of the pristine and damaged/debonded beams. The absolute differences between the measured NSCODs with and without damage/debonding are also shown in the inserted graphs in figure 9. It can be seen from figure 9(a) that difference in the measured NSCO for specimen A and C vary gradually between sensor electrode strips 1 to 7 and peaks at sensor electrode strip 3, which indicates the presence of the left end of the delamination. Due to the influence of incidental debonding at the sensor electrode strips 12 and 13, the right tip of the delamination could not be identified. As shown in figure 9(b), the presence of sensor edge debonding edge renders the capability to identify the left
end of the delamination in specimen B. However, the presence of the right delamination tip can be identified from the gradual variation and peak value at the sensor electrode strip 13 of the difference in the measured NSCO for specimen B and C. It is worth noting that the scatter of NSCO in figure 9 can be determined from that in figures 7 and 8.

Testing results for mode 2 are not presented as they are less sensitive to the presence of the delamination and debonding [18].

Figure 7. Measured sensor charge output distribution of the 1st mode for all specimens
Figure 8. Measured sensor charge output distribution of the 3\textsuperscript{rd} mode for two specimens

4. Conclusion
This study presents a surface strain distribution based method for identifying delamination in composite beams by using three specimens. The experimental results demonstrate that monitoring the sensor charge output based the surface strain distribution along the custom-designed sensor for modes 1 and 3 of the considered composite beam is a feasible approach to detect and locate an embedded delamination. The following points were illustrated:

- The difference in sensor charge output between a pristine and a delaminated beam peaks near a delamination tip decreases gradually when moving away from the delamination tip. The non-dimensional SCO distribution appears to be a better index for detecting and locating the delamination tip than the SCO;
- The measurement of sensor voltage output for mode 1 can be repeated with small standard deviation error whereas such error is large for mode 3;
- Debonding between a PZT sensor and its host structure tends to set the reading of the relevant sensor electrode strips to zero for edge debonding or a close to zero constant for a mid sensor debonding. The presence of sensor debonding near a delamination tip renders its ability to identify the location of delamination tips; and
- The sensitivity of damage detection varies with sensor and delamination location. For different vibration modes, the effect of sensor and delamination location on the damage detection sensitivity is different. The present results show that mode 1 has the most stable sensitivity and mode 3 has the most sensitivity.
Figure 9. Comparison of measured non-dimensional sensor charge output distribution

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