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Damage detection and its severity estimation by experimental and FEM approach using piezoelectric polymer film sensors

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ABSTRACT

The aim of this work is to experimentally investigate the ability prepared PVDF film sensor bonded on aluminium cantilever beams each having cracks at different locations with increasing crack depths for observing the ability of the film to indicate it with its film voltage response. The produced PVDF film sensor is bonded to a cantilever beam with araldite klear solution. Then with the help of impact hammer the beam is excited and voltage responses are noted down. The modal behaviour of beam and piezo-response is monitored by experimental measurement and is supported by the finite element analysis.

I. Introduction
The researches on the utilization of piezoelectric transducers as structural health monitoring (SHM) device and as an actuator are receiving huge attraction these years. To understand how these smart structures are beneficial it is important to comprehend its two major applications: as a sensor and as a actuator. Piezoelectricity was found around the 18th century by the two Frenchmen siblings, Pierre and Jacques Curie. The electric charge that generates in the materials in response to applied mechanical stress is called direct piezoelectric effect (sensor application). And the reverse of above phenomena is called converse piezoelectric effect (actuators).

II. Mechanical behaviour of the film
Young's modulus and maximum load carrying capacity and poisson ratio assumes

significant part in sensing and activation. With a specific end goal to examine these values for our produced film, the uni-axial tensile examination test with the utilization of computer aided machine available. Mechanical properties of the film are tested to determine its modulus of elasticity, maximum tensile strength which is utilized for the FEM analysis and also required for the selection of the suitable film for our experiment. Using electronic tensometer all the values were obtained for three samples: 75x25x0.028mm, 70x25x0.030mm and 75x25x0.032mm.

(a) (b) (c)

Fig1: (a) Electronic tensometer (b) Prepared film test samples (c) Samples held under roller chucks

Table 1: Mechanical properties of PVDF films

Sample Thickness (microns)	Maximum load (N)	Maximum tensile stress (Mpa)	Maximum tensile strain (mm/mm)	Tensile strength (Mpa)	Young's modulus (Gpa)
28µ	49.05	0.0280	0.0114	0.0167	1.957
30µ	78.46	0.0448	0.0189	0.0224	2.196
32µ	117.68	0.0672	0.0178	0.0392	2.540

The above readings were obtained on the basis of the four iterations of each. The results obtained for each test if plotted produced U-kind of curve which is usually seen in the composite materials. As this is a polymer composite material so this kind of curve was expected, this proves that the films are non-linear elastic materials. Also in present work the young’s modulus lies in between 1.957 to 2.54 GPa and the literature shows young’s modulus ranging from 2.5 GPa to 3.0 GPa

III. Crack size and depth measurement apparatus

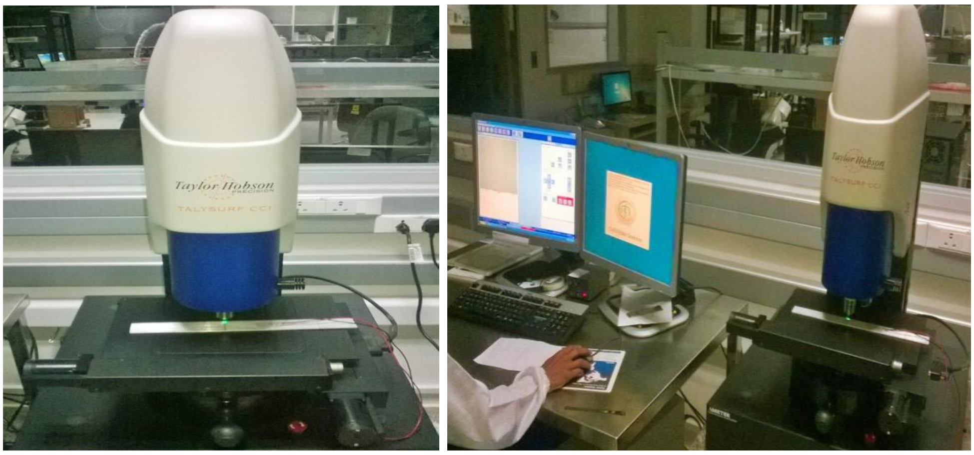


Fig. 2: Tylor Hoboson Talysurf 3D HD microscope to measure and achieve accurate crack size and depth: (a) optical microscope (b) machine setup

IV. Experimental test setup and procedure

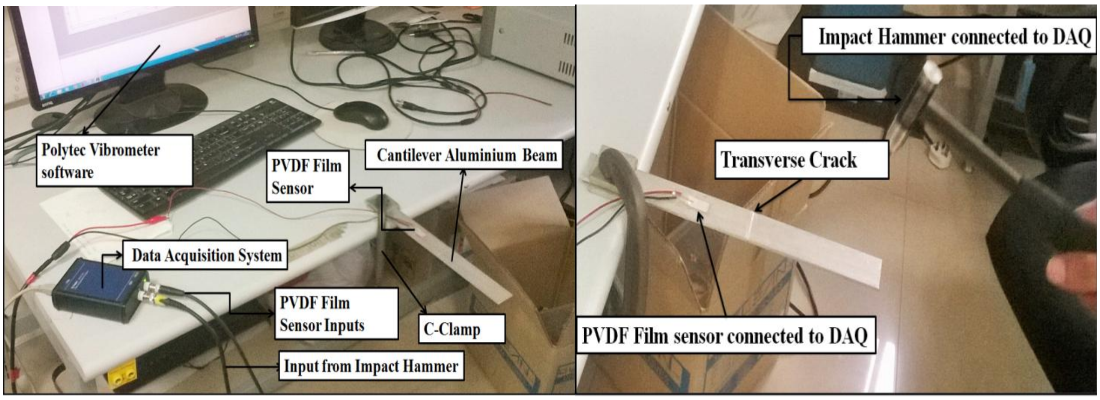


Fig. 3: Experimental setup for crack and its depth estimation

Experimental setup is as shown in the figure which involves a 25x2.5x0.03cm cantilever beam bonded with 1.5x1x0.0028 cm PVDF film sensor, Data Acquisition System (DAQ), an integrated hammer and Polytech vibrometer software for monitoring the film response.

The aluminium beam is excited with the impact of the hammer and the response is noted for these four different cases:

1. Intact cantilever beam (without any crack, scratches and voids)
2. Cantilever beam with transverse crack at 12.5cm from fixed end.

- At four different crack depths (0.5mm, 1mm, 1.5mm, 2mm)

3. Cantilever beam with transverse crack at 5cm from fixed end.
- At four different crack depths (0.5mm, 1mm, 1.5mm, 2mm)
4. Cantilever beam with transverse crack at 20cm from fixed end.
- At four different crack depths (0.5mm, 1mm, 1.5mm, 2mm)

V. Finite element method analysis

The same is solved with numerical approach for the validation of the experiment results using ANSYS Workbench 15.0. Both the elements are modelled using CATIAV5 CAD software and imported into the analysis software and solved for modal and electric analysis.

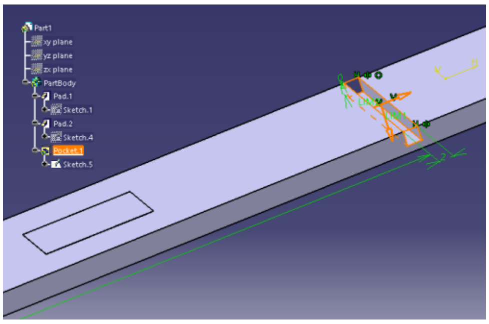


Fig. 4: CATIA V5 modelling

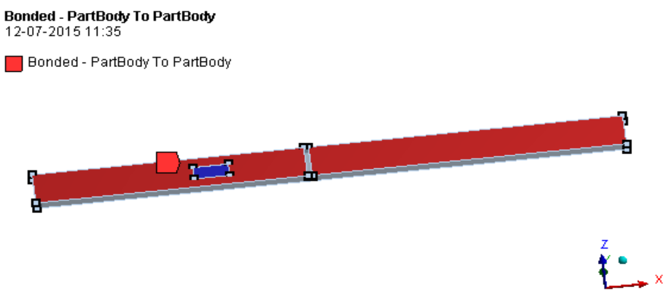


Fig. 5: PVDF bonded to Aluminium

Table 2: Material properties

Properties		Al Composite Beam	PVDF
Element selection in ANSYS		Solid 186	Solid 226
Young's modulus 'E'		69 Gpa	2.1 Gpa
Poisson's ratio		0.33	0.33
Density 'ρ'		2700	1780
Piezoelectric constants	d_{31}	-	22
	d_{32}	-	2.3
	d_{33}	-	-26

Table 3: Dimensional parameters

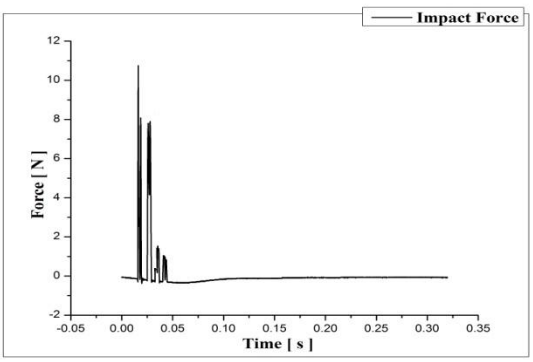
Parameters	Dimensions
Length of beam	250 mm
Breadth of beam	25 mm
Thickness of beam	3 mm
Length of PVDF sensor	15mm
Breadth of PVDF sensor	10mm
Thickness of PVDF sensor	0.028mm

VI. Results

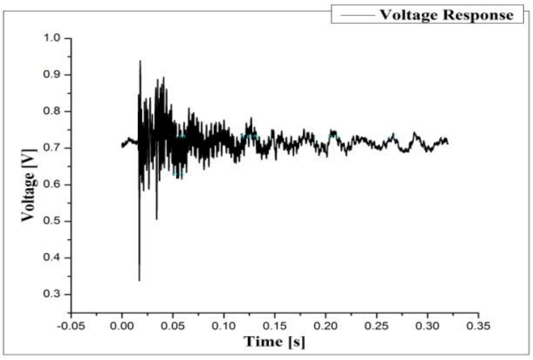
The voltage response by the film when the composite beam is hit by the impact of the hammer is well displayed in the graph plots. This response is processed using polytech vibrometer software and when done, the Fast Fourier Transformation (FFT) of the signal gives results in frequency domain with peaks in the graphs indicating modal frequencies of the beam. This frequency results are utilized to estimate the presence of the damage and its severity by comparing it with the intact and preceding case results.

Case 01: Intact cantilever Aluminium beam

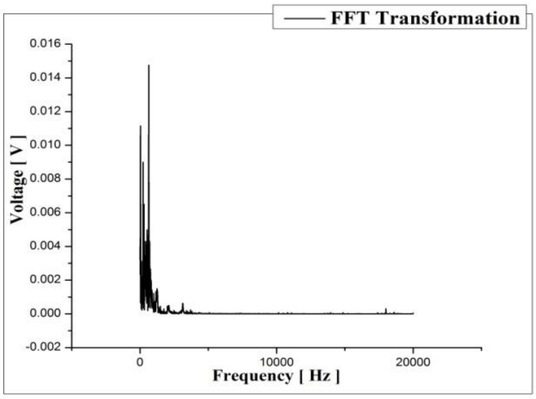
A. Experimental results



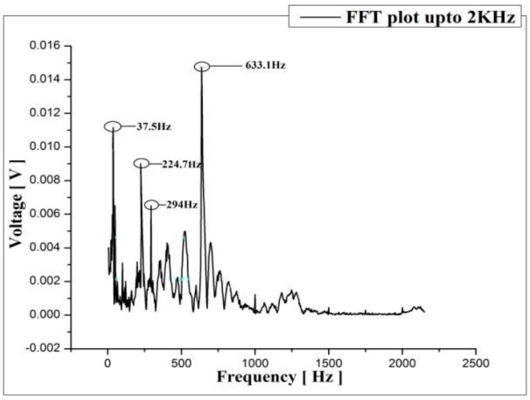
Graph 1: Impact force from the hammer



Graph 2: PVDF film voltage response to impact



Graph 3: FFT of the voltage response



Graph 4: FFT up to 2 KHz to indicate peaks

Following are the ANSYS modal analysis results for the comparison and validation of the experimental results.

B. ANSYS results

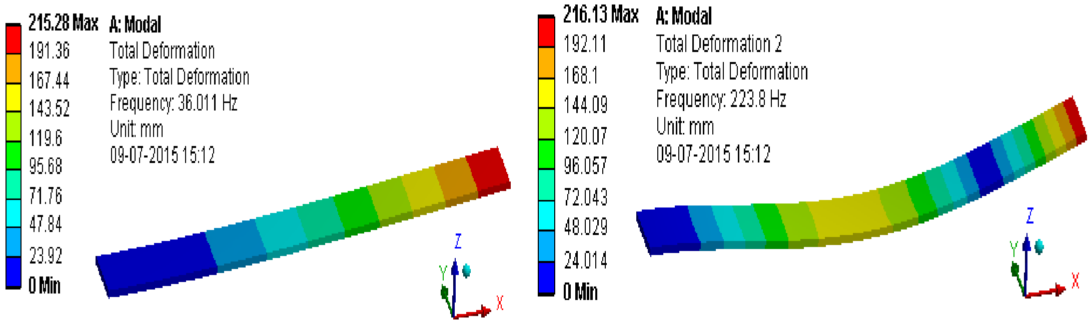
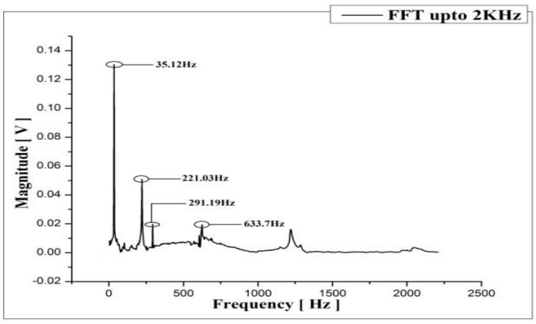


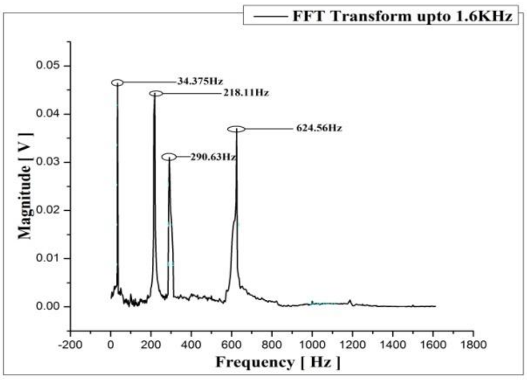
Fig. 6: Mode shapes with frequencies for an intact cantilever beam

Case 02: Beam with transverse crack at 12.5 cm from fixed end

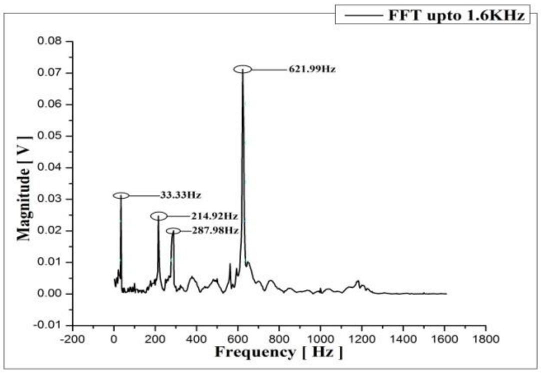
A. Experimental results



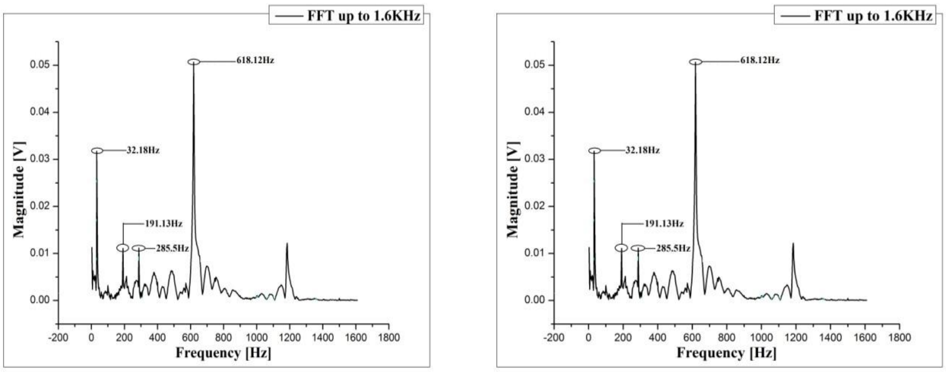
Graph 5: FFT plot for 0.5 mm crack depth



Graph 6: FFT plot for 1 mm crack depth



Graph 6: FFT plot for 1.5 mm crack depth



Graph 7: FFT plot for 2 mm crack depth

B. Comparison and validation

Table 4: Comparison to indicate the severity of crack at 12cm and validation by ANSYS

Mode No.	Results type	Intact Beam	Crack at 12.5cm from fixed end of a cantilever with increasing crack depths(4 depth positions)			
			0.5mm	1mm	1.5mm	2mm
01	Experimental	37.5Hz	35.12Hz	34.375Hz	33.33Hz	32.18Hz
	ANSYS	36.011Hz	35.672Hz	35.496Hz	35.112Hz	33.627Hz
02	Experimental	224.7Hz	221.15Hz	218.15Hz	214.92Hz	191.13Hz
	ANSYS	223.8Hz	222.29Hz	219.18Hz	212.91Hz	192.75Hz
03	Experimental	294Hz	291.89Hz	290.63Hz	287.98Hz	285.5Hz
	ANSYS	293.18Hz	292.78Hz	292.09Hz	290.57Hz	286.97Hz
04	Experimental	633.7Hz	628.11Hz	624.56Hz	621.99Hz	618.12Hz
	ANSYS	631.6Hz	626.3Hz	625.65Hz	624.13Hz	620.24Hz

Similarly, results are obtained for remaining two cases by both experimental and numerical approach and are tabulated below:

Case 03: Beam with transverse crack at 5 cm from fixed end

Table 5: Comparison to indicate the severity of the crack at 5cm and validation by ANSYS

Mode No.	Results type	Intact Beam	Crack at 5 cm from fixed end of a cantilever with increasing crack depths(4 depth positions)			
			0.5mm	1mm	1.5mm	2mm
01	Experimental	38Hz	38.733Hz	37.873Hz	35.873Hz	32.777Hz
	ANSYS	36.011Hz	40.391Hz	39.867Hz	38.17Hz	34.029Hz
02	Experimental	224.7Hz	231.04Hz	230.89Hz	229.88Hz	221.45Hz
	ANSYS	223.8Hz	234.54Hz	232.55Hz	232.24Hz	223.64Hz
03	Experimental	294Hz	291.98Hz	290.91Hz	286.93Hz	281.64Hz
	ANSYS	293.18Hz	294.01Hz	292.9Hz	288.64Hz	283.58Hz
04	Experimental	632.011Hz	653.06Hz	634.22Hz	645.71Hz	624Hz
	ANSYS	631.6Hz	657.45Hz	662.73Hz	657.65Hz	621.59Hz

Case 04: Beam with transverse crack at 20 cm from fixed end

Table 6: Comparison to indicate the severity of the crack at 20 cm and validation by ANSYS

Mode Set	Results type	Intact Beam	Crack at 20 cm from fixed end of a cantilever with increasing crack depths(4 depth positions)			
			0.5mm	1mm	1.5mm	2mm
01	Experimental	38Hz	38.122Hz	38.01Hz	35.17Gz	33.438Hz
	ANSYS	36.011Hz	36.603Hz	35.84Hz	35.834Hz	36.635Hz
02	Experimental	224.7Hz	223.55Hz	221.62Hz	231.14Hz	238.33Hz
	ANSYS	223.8Hz	229.43Hz	226.4Hz	224.81Hz	263.03Hz
03	Experimental	295Hz	291.86Hz	289.91Kz	286.91Hz	283.93Hz
	ANSYS	293.18Hz	294.43Hz	294.4Hz	294.8Hz	295.44Hz
04	Experimental	633.7Hz	655.63Hz	649.13Hz	639.44Hz	698.95Hz
	ANSYS	631.6Hz	680.63Hz	656.15Hz	641.1Hz	704.8Hz

A. Validation of voltage response

The voltage response is validated numerically by using couple field analysis in ANSYS Workbench by linking the modal analysis results with the electric analysis. After solving for the linked modal analysis, the electric analysis gives the voltage produced at each mode set.

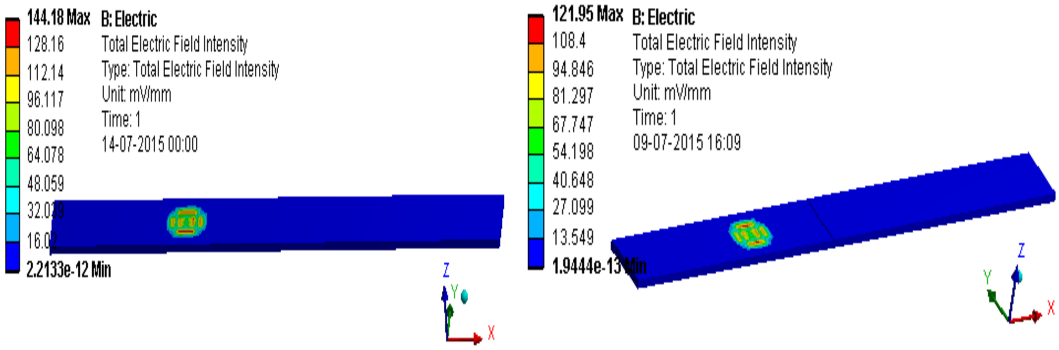


Fig. 7: Voltage produced at the 1st mode by: (a) intact cantilever composite beam, (b) cantilever with 0.5mm deep crack at 12.5cm from fixed end, (c) cantilever with 0.5mm deep crack at 12.5cm from fixed end and (d) cantilever with 0.5mm deep crack at 12.5cm from fixed end

Table 7: Validation of the experimental results with ANSYS voltage results

Case no.	Description of the cases	Experimental results	ANSYS results	Difference
		Voltage produced at first mode		
01	Intact cantilever beam	0.011157V	0.14418V	0.13302
02	0.5mm notch at 12.5cm	0.130442V	0.12195V	$8.492x10^{-03}$
03	0.5mm notch at 5cm	0.150015V	0.15361V	$3.595x10^{-03}$
04	0.5mm notch at 20cm	0.179112V	0.18093V	$9.81x10^{-03}$

VII. Conclusion

This study provided useful procedure for prepared PVDF film sensor in damage indication and its severity estimation. It was seen that in the beam with crack at 12.5 cm from fixed end (5cm ahead of film position), the film responded spontaneously with minimum errors when compared with ANSYS results. It also gave satisfactory results for the crack at 5 cm from fixed end (2.5cm before film position) but not as good as case one result because of the crack position before the film. Hence I would conclude that the prepared film proves its damage and its criticality sensing ability and the drawback of the film, which is accuracy level depending on the crack position is solved by increasing the number of sensors on the test structure.

VIII. References

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