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Energy harvesting potential of bendable concrete using polymer based piezoelectric generator

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ABSTRACT

Piezoelectric materials have gained a lot of attention in the last few decades as they introduce a renewable and sustainable approach for energy harvesting from vibrations or mechanical deformation in our environment. Among piezoelectric materials, polyvinylidene fluoride (PVDF) is one of the most commonly used piezoelectric polymers due to its high flexibility and piezoelectric performances. In this work, engineered cementitious composites (ECC) incorporating flexible PVDF based piezo polymer has been investigated as an innovative energy harvesting system to scavenge energy from mechanical deflection of ECC. Synchronous flexural test and voltage data recordings were employed to evaluate the voltage capture efficiency of two different lengths of PVDF (41 mm and 73 mm). The various loading rates of four-point bending tests were conducted to assess the energy harvesting performance. The results show that the voltage/power generated by the system is more efficient for longer PVDF samples as compared to the shorter ones when subjected to the four-point flexural test. High loading rates were found to be favorable for energy harvesting. The experimental results lay a solid foundation for potential energy harvesting application of the new cementitious composite system for development of multi-function building materials.

1. Introduction

Energy harvesting from regenerative power technologies is the process of converting energy from the ambient environment through certain materials and devices that have distinctive material properties such as piezoelectric [1–3], thermoelectric [4–8], triboelectric [9], electromagnetic [10–13], and photovoltaic [14,15] or hybrid functional [16] properties. For harvesting energy from mechanical vibration, piezoelectric, electromagnetic and triboelectric materials can all be implemented. Among them, piezoelectric materials are the most explored since they have relatively high energy density when compare to the other materials [17], and mechanical energy is abundant.

Lead zirconate titanate (PZT) is the most widely used piezoelectric ceramic material and has found many applications in structural health monitoring sensing systems [18]. However, the intrinsic brittleness of the material is a major drawback as it limits its application in high strain structures or conditions as in the case of civil infrastructure and buildings. On the contrary, Polyvinylidene Difluoride (PVDF) is the most popular commercial flexible piezoelectric polymer material because it has high ductility remarkable mechanical properties, and excellent piezoelectric performance. This single crystalline polymer is formed by the repeated monomer unit $(-C_2H_2F_2-)_n$, and has four peculiar crystal structures which includes polar crystal forms (β, γ, and δ phases) and non-polar phases(α-phase). Among the phases, β-phase (TTTT) is comparatively more polar than the others, which is favorable for piezoelectric materials [19]. The voltage generated by β-phase PVDF is about 10–25 times higher than that of piezo-ceramics for the same pressure input condition [20]. Such favorable properties make PVDF a promising potential candidate for applications in structures that may undergo large deformations since flexible materials can withstand comparatively higher deformation without breaking. Jiang et al. utilized the laminated PVDF cantilever with the magnet for harvesting low frequency vibrations [21]. Vantansever et al. compared the performance of PVDF and PZT for energy harvesting and found that piezopolymer PVDF can generate higher voltage/power than piezoceramic PZT [22].

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Civil Engineering infrastructure provides massive avenues for potential energy harvesting through large scale vibrations or structural deformation. Dynamic loads on structures due to effects of traffic, wind, earthquakes, waves and human motion produce vibrations [18] which can be harnessed and stored for various applications. One of the potential areas for energy harvesting through civil structures is using piezoelectric materials to convert vibration in long-span bridges. Cahill et al. studied the possibility of harvesting energy from vibrations induced in bridges by trains over it. The researchers utilized and compared results obtained from PZT and PVDF sensors [19]. The findings showed that these materials can not only be used for energy harvesting application but also for sensing defects in the structure. Moreover, tuned Mass Dampers (TMD) used in tall buildings and earthquake resistant structures to overcome the action of winds and seismic action, are another promising source for harvesting vibration energy. Tang et al. demonstrated the dual purpose of a regenerative TMD in controlling vibration in a three-story structure while simultaneously harvesting energy from the vibrations [18].

Further, vibrations in buildings could also be induced on a large scale by earthquakes. When a building undergoes seismic loading, the excitation energy of the earthquake acts on the structural members, and reactions such as displacement and deformation develop. Once the seismic energy is higher than the energy capacity that the structural member can withstand, it might fail. Floods and fires are some major hazards caused by earthquakes, which in turn can lead to the breakdown of power lines. Flexible piezopolymer devices with self-supplied or self-powered ability can serve as a potential solution under such circumstances to either power sensing systems or to provide power to charge communication devices or other small electronic devices. Quasi real-time monitoring of the structure during an earthquake can also prove to be very beneficial during post-earthquake building inspection, resulting in efficiency through conservation of time. Kurata et al. utilized PVDF films as dynamic strain sensors in steel moment-resisting frames to detect local damage [20]. Suzuki et al. further quantified local damage in floor slabs and steel beams by using PVDF sensors as dynamic strain sensors [21].

When reinforced concrete structures are subjected to seismic loading or large deformations, the tensile resistance of the reinforcement becomes important only after concrete cracking. In other words, once the first crack is formed, the crack will extend in width rather than propagate before the rebar is engaged. Even highly flexible materials for energy harvesting from RC structures cannot withstand very large deflections. One way to overcome this challenge could be using Engineered cementitious composites [23–26] (ECCs), which are a unique type of high-performance fiber reinforced cementitious composites [27,28] with pseudo strain-hardening behavior under flexural and tensile loading. The tensile strain capacity of typical ECC is often above 2%. Moreover, the intrinsic hairline crack-width control property can limit the crack of ECC to be less than 60 μm before failure. In combination with these improved cracking properties of concrete using ECC, flexible piezoelectric materials can be used for energy harvesting.

Although some researchers have studied the application of PVDF for energy harvesting from regular RC infrastructures [29] or renewable sources such as wind and water droplets [22], little research has been done to investigate its application in energy harvesting through bendable construction materials. This research proposes to utilize a piezoelectric energy harvesting structural system using ECC equipped with piezo-generator - PVDF, which can harvest energy from structures for emergency electricity provision during disasters such as earthquakes or for powering the street light on the bridge/pavement. The system is designed to take advantage of the extraordinary flexural performance of concrete composed of ECC for generating electricity through PVDF. By conducting four-point bending tests with real-time monitoring of the voltage generated by PVDF, which was bonded on the ECC specimen, the electric harvesting performance was evaluated, and further, the relationship between flexural deformation and the voltage generating efficiency was determined. The preliminary experiment was done to estimate the effectiveness and potential of the cement-based energy harvesting system for future research on full-size structural members.

Table 1
Mixture proportions (by weight).

Mixture	Cement	Fly ash	Silica sand	water	Superplasticizer	PVA Fiber (by volume)
ECC	1	1.2	0.8	0.5	0.008	2%

2. Specimen preparations and experiment setup

2.1. Materials

Table 1 presents the relative proportions by weight and ingredients of ECC used in this study. Type I Ordinary Portland cement, class C fly ash, silica sand and PVA fiber have been utilized for mixing the ECC. The mixture has been extensively used in literature [30,31]. The maximum particle size of the silica sand used in this research is 0.2 mm. Two percent volumetric fractions of polyvinyl alcohol fiber, 39 μm in diameter and 8 mm in length, was also added to the ECC. The properties of PVA fiber are shown in Table 2. For enhancing the workability of the cementitious composite, polycarboxylate based superplasticizer was added.

2.2. Mixing cementitious materials and bonding the energy harvester

Ingredients for the ECC specimens were mixed in a Hobart mixer. The mixing procedure of ECC is shown in previous work [32]. After mixing, the fresh ECC was cast into plastic molds to make the 2.54 cm × 6 cm × 21 cm specimen. The specimens were demolded after 24 h and water cured at the room temperature of (23 ± 2 °C) until test.

PVDF was bonded on the specimen at the mid-span of the bottom surface as shown in Fig. 1. In this study, two different lengths of PVDF (41 mm and 73 mm) with width of 16 mm and thickness of 40 μm were used for size-based performance comparison. The dimension details of PVDF film device are presented in Table 3. The rectangular shaped film elements were made with silver ink screen-printed electrodes for metallization. The thin polyurethane was used as protective coating to prevent oxidation of the surface of the electrode area. Lead components were bonded to the sensor using 12″ riveted lugs connected with 28 AWG wire. The properties of PVDF are listed in Table 4. The manufacturer indicated that the PVDF can generate more than 10 mV per micro-strain. The output voltage of PVDF is from 10 mV to100 V depending on force and circuit impedance (see Fig. 2 and Table 5).

2.3. Experiment setup

Four-point bending test was conducted to evaluate the flexural properties of ECC. The experimental load span of the specimen is 50 mm (one third of the support span 150 mm). Flexural deformation is imposed on the surface of the specimen by the MTS servo-hydraulic system. Three different loading rates of 0.5, 1.0, 2.0 mm/min were applied on the samples with short PVDF and long PVDF, named S1, S2, S3, and L1, L2, L3 respectively. Voltage data logger - Adc-20 with the

Table 2
Material properties of PVA fiber.

Type	Diameter (μm)	Length (mm)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Specific Gravity
RECS-15	39	8	1600	41	1.3

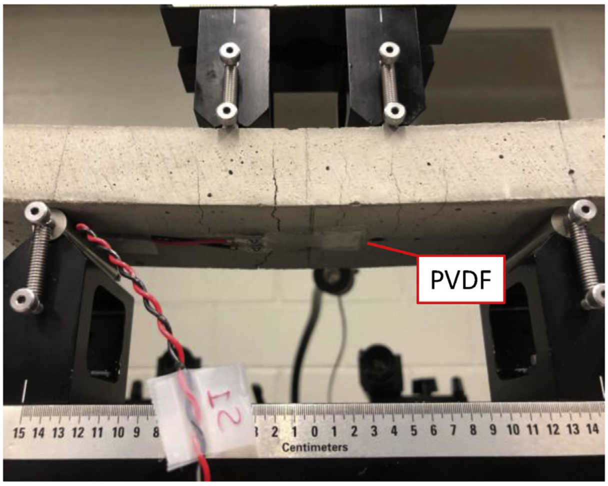


Fig. 1. 4-point flexural test specimen.

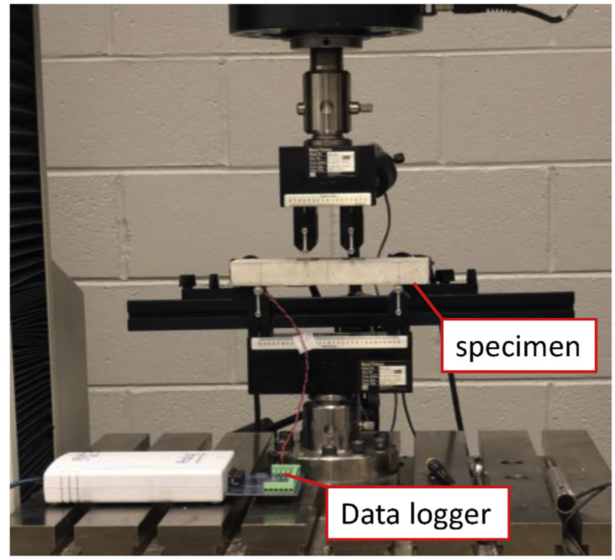


Fig. 2. The setup for 4-pt bending test.

Table 3
Dimension of PVDF sensor (Measurement Specialties, Inc.).

	Film Width (mm)	Film Length (mm)	Film Thickness (μm)	capacitance (nF)
Short PVDF (S)	16	41	40	1.38
Long PVDF (L)	16	73	40	2.78

Table 4
Material properties of PVDF (Measurement Specialties, Inc.).

Parameter	Symbol	Value	Unit
Piezo Charge Const.	d_{31}	23	pC/N
	d_{33}	−33	
Piezo Voltage Const.	g_{31}	216	V mm/N
	g_{33}	−330	
Electromechanical Coupling Factor	k_{31}	12%	–
	k_t	14%	
Young's Modulus	E	2–4	GPa
Yield Strength	–	45–55	MPa
Pyroelectric Coeff.	P	30	$C/m^{2}°K$
Permittivity	ϵ	106–113	F/m
Relative Permittivity	ϵ/ϵ_0	12–13	–
Mass Density	ρ	1.78	10^3 kg/m
Volume Resistivity	ρ_θ	$> 10^{13}$	Ω-m
Temperature Range	–	−40 to 100	°C
Water Absorption	–	< 0.02	%

terminal board was utilized to record the real-time voltage output simultaneously. Output voltage data was recorded per millisecond. The experimental setup is shown in Fig. 3.

3. Results and discussion

Table 6 shows the experimental results of four-point bending energy harvesting test. The average ultimate flexural strength of the samples is 4.62 MPa and the elastic modulus is 28 GPa. Each specimen presents relatively good flexural capacity with fair mid-point displacement. The change of loading rate from 0.5 mm/s to 2.0 mm/s does not show any appreciable effect on the ultimate flexural strength and mid-point displacement in this study. However, the cumulative output voltage increased with the increase of the loading rate for both short PVDF and long PVDF samples except the sample S2 with loading rate of 1.0 mm/s. The location of major crack for S2 developed next to the PVDF harvester. This resulted in the short PVDF piezo-sensor being unable to

Table 5
Samples with different loading rates.

Sample	S1	S2	S3	L1	L2	L3
Loading rate(mm/s)	0.5	1.0	2.0	0.5	1.0	2.0

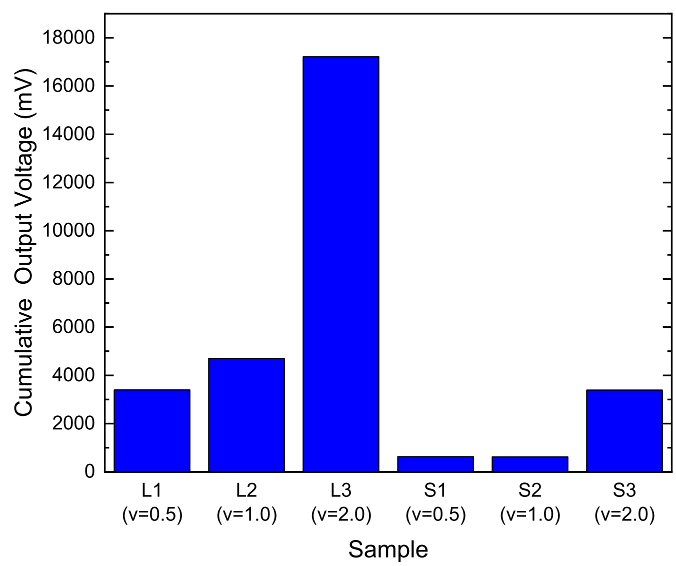
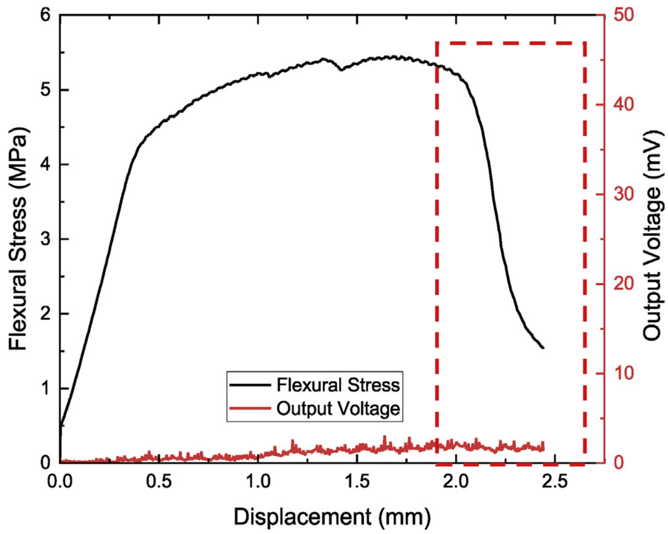


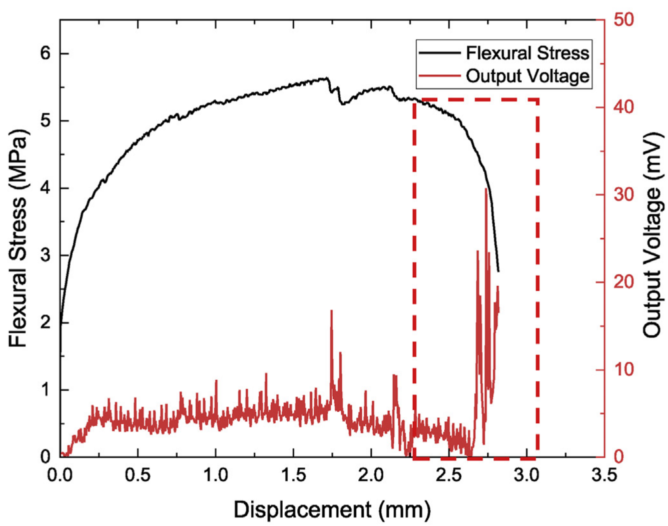
Fig. 3. Cumulative output voltage of different samples (v: loading rate).

Table 6
Result of four-point energy harvesting test.

Sample	Loading rate (mm/s)	Ultimate flexural strength (MPa)	Mid-point displacement at ultimate flexural strength (mm)	Cumulative output voltage (mV)
S1	0.5	5.45	1.73	626
S2	1.0	3.18	0.53	620
S3	2.0	4.86	1.19	3392
L1	0.5	5.64	1.72	3397
L2	1.0	5.01	2.33	4701
L3	2.0	3.50	0.89	17218

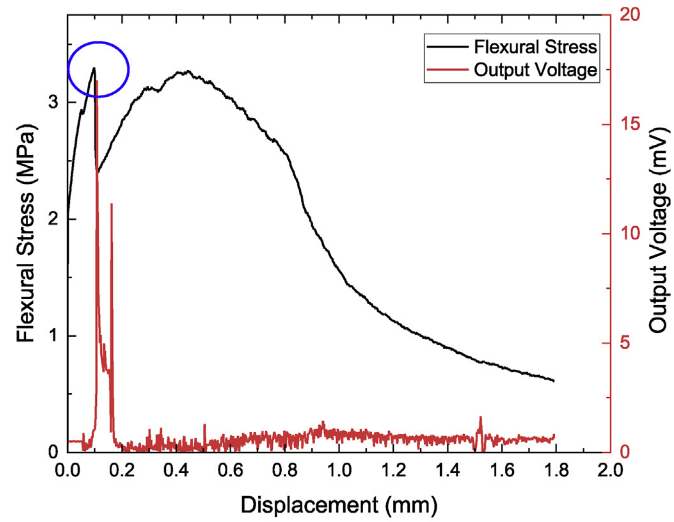


(a) S1

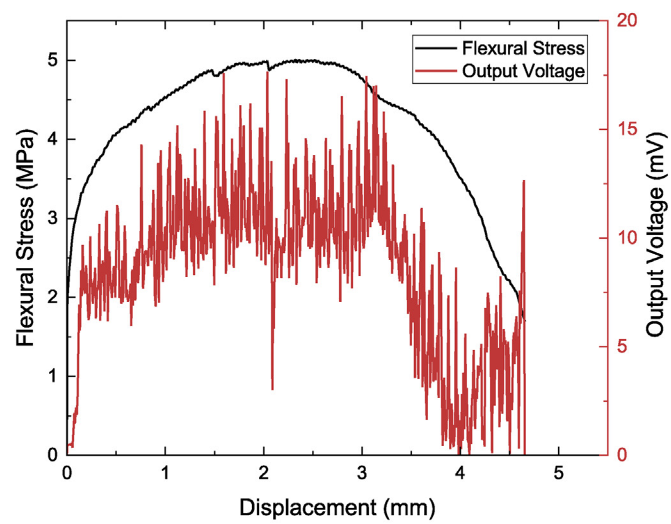


(b) L1

Fig. 4. Flexural Stress –output voltage-displacement curve of the samples with 0.5 mm/s loading rate.



(a) S2



(b) L2

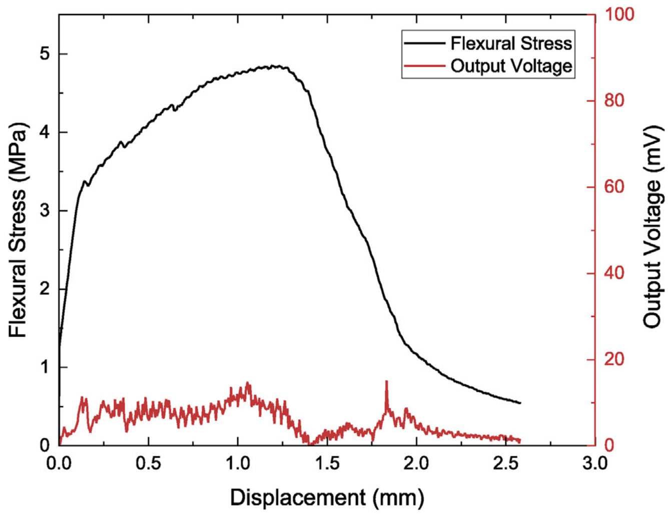
Fig. 5. Flexural Stress –output voltage-displacement curve of the samples with 1.0 mm/s loading rate.

capture the flexural strain of the specimen. The cumulative output voltage of the sample with high loading rate (S3 and L3) was greater than the other samples by 3–5 times. This is probably because the low loading rates of 0.5 and 1 mm/s are more like static loading conditions, hence the piezoelectric properties of PVDF could not be fully exploited. The histogram in Fig. 3 displays the cumulative output voltages of each sample. The electricity harvested by long PVDF samples (L1-L3) was 5–7 times higher than the short PVDF harvesters, since larger the area covered by piezoelectric materials, higher is the energy that can be harvested.

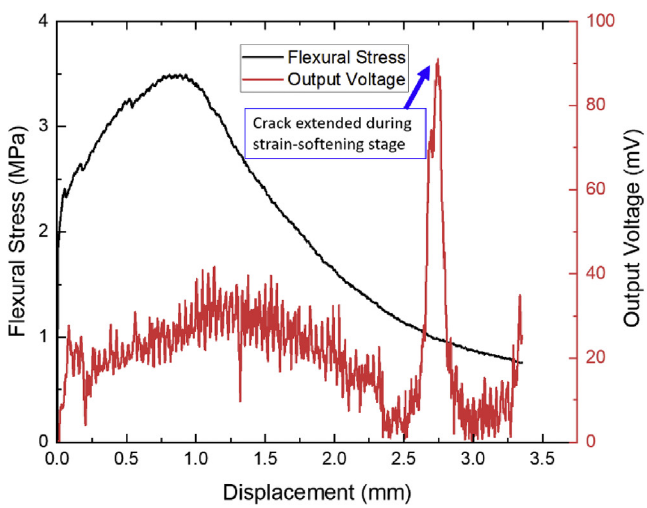
Fig. 4 presents the flexural stress–displacement curve and output voltage-displacement curve under the 0.5 mm/s loading rate condition. The black solid line indicates the flexural stress and displacement curve which should refer to the left black y-axis, and the red solid line is the curve of the relationship between output voltage and displacement which should refer to the right red y-axis. It is found that as the sample is undergoing strain-softening behavior (red box on Fig. 4), the output voltage of L1 at displacement 2.7 mm increased to 30 mV, which means the sample with long length PVDF could still capture the strain induced by the extended cracking. Although the energy S1 acquired was not as much as L1, the output voltage still increased with increasing displacement.

The result of samples with 1.0 mm/s loading rate is displayed in Fig. 5. The output voltage axis of Fig. 5 scaled from 50 down to 20 as compared with Fig. 4. It can be observed more clearly that the voltage harvested by L2 is approximately 7 times greater than S2. It is worth mentioning that as the large crack began to appear and propagate on sample S2, the stress dropped as shown from the blue circle of Fig. 5 (a), this phenomenon is not only seen in the stress-displacement curve but can also be observed on the output-displacement curve as the voltage peak, which indicate that PVDF have the high sensitive for crack detecting in structural health monitoring.

High loading rate results are shown in Fig. 6. It can be seen that the high loading rate made the sample enter the strain-softening stage earlier than the other samples because it achieved the peak stress earlier. It is interesting to note that the high voltage peak in Fig. 6 (b) (at



(a) S3



(b) L3

Fig. 6. Flexural Stress –output voltage-displacement curve of the samples with 2.0 mm/s loading rate.

blue arrow) indicates the crack extended largely during the strain-softening stage.

4. Conclusion

The concept of innovative energy harvesting structural material system using PVDF-ECC for converting large deformations into electricity has been proposed in this study. The preliminary experiment has been conducted for assessing the feasibility and potential of the PVDF-ECC system. The influence of two different lengths of PVDF on voltage output was investigated. Energy harvesting efficiency of various loading rates of four-point bending test was also studied and discussed. For the two-different lengths of PVDF, the cumulative output increased with the increase of loading rate except for sample S2 where a major crack developed right next to the PVDF. The samples with high loading rate (S3 and L3) 2 mm/s can generate 3–5 times more voltage than the other samples with relatively low loading rate. The result might be attributed to the fact that a loading rate of 0.5 or 1 mm/s is more like a static loading condition, which was not favorable for the piezoelectric performance.

Cumulative electricity output of the long length PVDF samples were higher than the short ones by 5–7 times which indicates the more area covered by piezoelectric materials, the higher the energy that can be harvested. The peak of output on the voltage-displacement figure shows that PVDF film sensor have high sensitive to detect the propagation of cracking on the covered area. This mean the flexible PVDF film have the potential on application of structural health monitoring especially for measure the crack in some critical part of structures such as beam-column joint etc.

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