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Optimization of Piezo-Fibre Composite with IDE Embedded in a Multilayer Glass Fibre Composite

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Abstract: This paper deals with studying the effect of positioning and number of PFC with IDE (PFC-W14) embedded in a multilayer glass fibre composite for energy harvesting. Vacuum Bagging process is used to fabricate eight Multi- layered composite with PFC-W14 embedded inside the specimen at different locations and numbers. The PFC-W14 is positioned at different layers of the composite and number of PFC-W14 is varied in order to study various cases of strain acting on composite. Vibration test for different frequencies were conducted on these eight specimen using electro-dynamic shaker. The generated energy is directly proportional to the strain or voltage generated along the perpendicular axis of the direction of the strain applied, which is collected by the Integrated Digitated Electrodes. The max frequency of vibration at which max voltage is generated by each specimen is observed for different locations and numbers. The results of this study are presented with an eye toward obtaining guidelines for design of useful energy harvesting structures.

Selection and peer review under responsibility of the Gokaraju Rangaraju Institute of Engineering and Technology (GRIET)

Key Words: Piezo-Fibre composite, Energy harvesting, smart structure, optimization.

1. Introduction

Energy is always essential in building up modern society. It is required everywhere from the household light bulb to a mission to Space. Some energy can be seen; light for example, but most do not have a visible form.

Nomenclature	
V	Voltage
Hz	Hertz
PFC	Piezo fibre composite
IDE	Integrated Digitated Electrodes
BNC	British Naval Connector

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Energy is defined in several ways, such as mechanical, electrical, and chemical. All of these definitions are based on where the energy is stored. Energy is stored everywhere. Heat, electricity, mechanical, chemical, photo, and biomass forms of energy are all stored differently, but can be converted from one to another. Among many types of energy, electricity is the most commonly used form for modern devices because it is easy to convert to other types. The term 'power generation' commonly refers to energy conversion from other energy forms to electrical energy.

There are many ways to complete electrical conversions. Photocells convert light to electricity, thermocouples convert heat to electricity, and magneto electric generators convert mechanical energy to electricity. These are all called power generators and are frequently used in electricity generation. Similar to magneto electric generators, piezoelectric generators (PEGs) can also convert mechanical energy to electrical energy. PEGs Vibration based energy harvesting is the most suited for UAV, smaller aircrafts, RC's etc as whenever aircrafts are flying at an altitude at a particular speed it induces vibration at various parts of the aircrafts. If we are able to generate power out of these vibrations it will lead to two types of advantages.

(a) Vibration damping

(b) Power generation using the vibration

If this can be achieved the requirement of an external power source as well as maintenance costs for periodic battery can be reduced.

There are three ways of harvesting vibration energy, Electromagnetic, electrostatic and piezoelectric. Piezoelectric system has received more attention than electromagnetic energy harvesting as they give very low output and often multistage post processing is required to reach a voltage level that can charge a storage component which makes it bulky. Another advantage of Piezo based energy harvesting system is piezoelectric devices can be fabricated both in macro-scale and micro-scale due to well established thick film and thin film fabrication techniques.

A great amount of research has been done in the analysis of piezoelectric materials and structures, as reviewed by Wen H.Ko (1969) presented one of the first suggested applications involving vibration energy harvesting using piezoelectric materials .US patent titled "Piezoelectric Energy Converter for Electronics Implants" in this, he proposed harvesting energy from heartbeats for use in powering implanted medical pacemakers by the use of cantilever piezoelectric beam with a tip mass.

Taylor.G.W and Burns.J.R (1983)presented one of the earliest published works in vibration energy harvesting with piezoelectric materials. They proposed the use of an array of polyvinylidene fluoride (PVDF) piezoelectric polymer film to harvest hydrodynamic energy from ocean waves. Although no physical system was proposed or built, it was theorized that a 100 MW power plant utilizing PVDF could deliver power to onshore grid at a cost of 2.5 cents per kWh.

Umeda et al. (1996) performed works to explore the fundamentals of impact energy conversion using piezoelectric materials. Umeda first developed an equivalent circuit model to predict the response of a piezoelectric vibrator plate when impacted with a steel ball. The existence of an optimal load resistance for maximum power transfer from the piezoelectric layers was shown in stimulation results. Much of the potential energy from the steel ball is transferred back to the ball when rebounding off of the vibrator plate, thus decreasing the efficiency of energy conversion. An experimental study to validate their previously developed model and also rectification and storage of the electrical outputs of the piezoelectric vibrator via a bridge rectifier and storage capacitor was performed by Umeda in the following year. Results of the experimental testing showed the ability of the piezoelectric vibrator to charge the storage capacitor using impact energy, and that for a capacitor pre-charged above 5V, an efficiency of 35% was achieved.

A novel concept is presented by Steven.R.Anton (2011) which involves the combination of piezoelectric devices and new thin film battery to form multifunctional self-charging, load bearing energy harvesting devices for use in UAV systems. The proposed self charging structures contain both power generation and energy storage capabilities in a multilayered, composite platform consisting of active piezoceramic layers for scavenging energy, thin film batteries for storing scavenged energy, and a central metallic substrate layer. The compact nature of the device allows easier integration into UAV systems and their flexibility provides the ability to carry load as structural members.

N.W. Hagood et al. (1990) of United States Patent designed a composite for actuating and sensing deformation. The composite have a series of flexible, elongated piezoelectric fibres arranged in a parallel array with adjacent fibres separated by relatively soft polymer. The piezoelectric fibres have a common poling direction transverse to their axial extension. The composite further includes flexible conductive material along the axial extension of the fibres for imposing or detecting an electric field.

"Piezoelectric Energy Harvesting with a Clamped Circular Plate: Analysis" by Sunghwan Kim et al. (2005) mentions about the small generation capability that has not been attractive for mass energy generation. He develops an increased interest in wearable computer concepts and remote electrical devices that has provided motivation for more extensive study of piezoelectric energy harvesting. The theory behind cantilever-type piezoelectric elements is well known, but the transverse moving plate elements, which can be used in energy generation from pressure sources is not yet fully developed. The power generation in a pressure-loaded plate depends on several factors. Among them, the thickness of each layer is important, as is the electrode pattern used. In this article, two clamped circular plate structures, a fully electroded unimorph, and a so-called regrouped electrode unimorph, are modeled. These models are then used to calculate energy generation with varying thickness ratios. The results of this analysis are presented with an eye toward obtaining guidelines for design of useful energy harvesting structures.

"Smart structures and piezoelectric materials" by S. Kamle refers to smart materials and structures that can assess their own health, perform self repair or can make critical adjustments in their behaviour as condition changes. He mentions about the helpful characteristics provided by a human body for the application of Piezo sensors and actuators. The results from the experiments indicate that the PVDF sensors and actuators show much promise for controlling acoustic radiation from the hood.

In this project effect of positioning and numbers of PFC-W14 at various layers of composite on voltage generation of the composite has been studied which leads to finding an optimal position of placing a Piezo fibre inside a multilayer composite to generate maximum voltage output.

2. Manufacturing

The manufacturing process was carried out at Advanced Composites Division, CSIR-NAL, Bangalore. The piezo fibre embedded composites are prepared by vacuum baggage process. Different configurations of the composite samples are prepared by placing PFC-W14 at different locations of the composite. Samples of different thickness are prepared. Samples with two of PFC-W14s are also prepared. These are for the comparison study of the samples based on the thickness, number of PFC-W14 in a single specimen, arrangement of PFC-W14 in a specimen and the position of PFC-W14 in the specimen.

2.1. Material selection

The following materials have been used for the fabrication of piezoelectric fibre embedded composite.

- Piezoelectric fibres : PFC –W14
- Glass Fibre : S-Glass Fibres
- Resin : Araldite CY 230-1
- Hardener : Aradur HY 951

2.2 Initial preparation

Once the materials have been selected we move on to the experimental apparatus used for the fabrication.

Apparatus mainly consist of:

- Vacuum pump
- Vacuum port
- Vacuum bag
- Oven

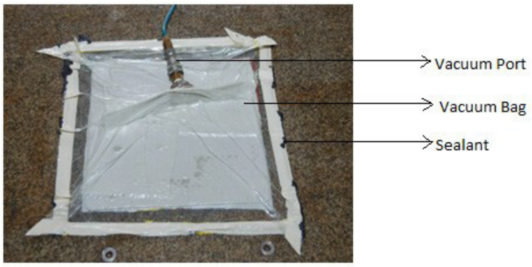

Fig.1. (a) Vacuum Baggage

A set of basic procedures are to be followed before the main fabrication is done. The basic steps carried out as at start-up for the process are as follows:

- Clean the table using acetone so as to make it dust free.
- Cut the breather, non porous layer, porous layer, peel ply to the required dimension of the composite needed.
- Hylam sheet that is curved at the edges is stuck to the table, as the base plate for the smooth and uniform surface.
- The vacuum bag is cut to the required dimension, and a double stick tape is used at the boundary to seal the bag and table.
- Clean the base plate and the surroundings by acetone.
- Wax (wooden polish) is applied to the base plate.
- Around the base plate, tape is stuck on the surface of the table and a non porous layer is stuck on top of it.
- Excess sheet of the layer is trimmed.
- The top end of the vacuum bag is stuck to the table.
- A hole is created on the vacuum bag to place the vacuum port.

2.3 Main Fabrication

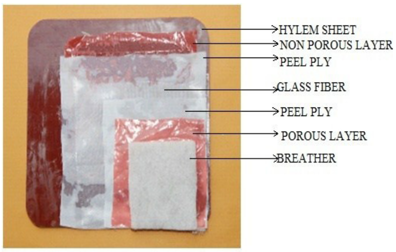

Fig.1. (b) Layers Used

According to the required dimensions of the specimens a template is cut, and strips of glass fibre cloth are cut. Then the weight of the glass fibre and peel ply is checked using electronic weigh balance. The weight of the material is noted and accordingly the resin-hardener is taken in a container with a ratio 100:10 and stirred well. Once the epoxy mixture is ready the fabrication process speeds up as the pot life of epoxy is 40 minutes. The glass fibre is placed on a sheet and epoxy mixture is applied on top of it. Then the sheet is folded, the template is placed on the top of the sheet and the sheet is cut to the template dimensions. Once the sheet is cut for the required dimension, the sheet is peeled out and the glass cloth is placed in the peel ply on top of the base plate. Then the epoxy is applied on the fibre and layers of the fibres are made according to the thickness of the specimen. The piezo fibre is placed on the top of the glass fibre layers. The electrode end of the piezo fibre is covered using flash breaker before placing it onto the glass fibres. Then the remaining glass fibres are placed on top of the piezo fibre in layers according to the thickness. Once the pasting of the layers using epoxy is complete, a peel ply is placed on top, followed by the porous layer. Then the breather is placed on top of the porous layer and the vacuum port is attached with the breather. The whole setup is covered with the vacuum bag and sealed using tape. The vacuum pump is connected to the vacuum port and the pump is switched on. A sample of the fibre is placed in the room temperature to check the curing rate. The vacuum pressure reading of 680 mmHg is noted and the setup is left to cure for 24-48 hours at room temperature.

After 48 hours the sample piece is observed to check the curing. If the sample exhibit brittle fracture then the composite is cured. Once the composite is cured the pump is switched off, and the vacuum bag is removed. The composite is taken out of the bag. The specimen is then placed inside the oven for 4 hours at 60^{o}C. Ensure that the thermocouple locations are below the component and peel ply is removed. Thus the composite is fabricated as shown in Fig.1. (c).

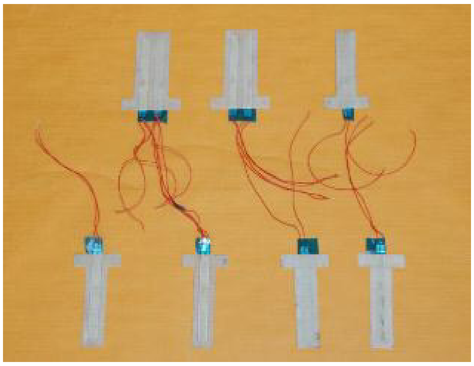

Fig.1. (c) Glass fibre composite specimens embedded with PFC-W14

3. Experimental Set Up

3.1 Testing apparatus

- Electro-dynamic Shaker
- Function generator
- Voltmeter
- Power Amplifier

Fig.2. Photo Representation of Electro-dynamic Shaker

Electro-dynamic shaker is an instrument used to carry out vibration testing. In this instrument controlled vibrations can be obtained. Frequency is given as an input. It reproduces ambient conditions for studies of endurance and reliability in all fields of vibration testing. The electro-dynamic shaker is supported in a rugged revolving frame for excitation in vertical or horizontal direction. A plunger is inserted at the top of the shaker by means of which the specimen is made to vibrate at different frequencies.

The electro-dynamic shaker used here is the “TIRA VIB”. Function generator is used to generate the input frequency and it is connected to the Power amplifier by means of BNC cables. The function generator used is the, “scientific generator HM5030”.The Power Amplifier Type BAA 120 has been designed to drive any vibration or modal exciter requiring a 120 VA power amplifier. The rated AC output is 120 VA into a 4 Ohm exciter or resistive load. The power amplifier has a useable frequency range from 40 Hz to 20 kHz (full capacity) or DC to 100 kHz (reduced capacity).The instrument can tolerate the temperature and supply line variation while maintaining excellent stability.

Fig.3. Photo Representation of Function generator

3.2 Testing procedure

The specimen is clamped on a suitable frame so that it acts as a cantilever beam. The frame is placed in such a way that the plunger just touches the tip of the beam. The specimen is clamped to the wooden frame very tightly using the C-clamp and the frame is held very firm so as to induce effective vibration into the specimen. The electrodes of the PFC-W14 are connected to the voltmeter by means of connecting wires. Function generator and Electro-dynamic shaker are connected to the Power amplifier.

It was found that some voltage is generated even before the vibration is commenced. This is due to the strain acting on the specimen when it is clamped to the frame. Initially, the values 0.1A and 0.3V are set in the Power amplifier. The sine wave is the input signal and the frequency is varied. The vibration frequency ranging from 0.8 to 30 Hz is applied in this case. For each frequency the voltage generated by the specimen is measured using the voltmeter. Special care is taken while connecting the wires to the voltmeter in case of specimens 3, 4 and 5 as they have two PFC-W14 in it. The voltage measured will be very less if the positive and negative wires are cross connected. The voltage generated is measured for all the 8 specimens. The result obtained are plotted with frequency along X axis and voltage along Y axis. The resonance frequency for each specimen is found from these values.

4. Results and Discussion

4.1. Effect of thickness of multi-layer composite on voltage generation by PFC-W14

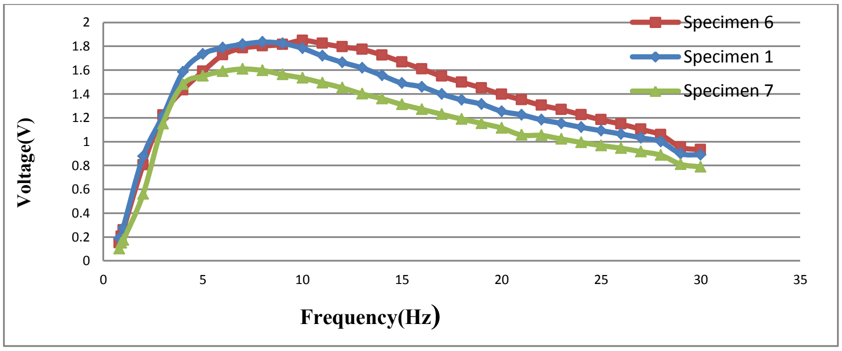

Fig.4. (a) Comparison Based on Thickness

Specimen 6 of thickness 1.1mm, specimen 1 of thickness 1.5mm and specimen7 of thickness 2.1mm with PFC-W14 embedded at exact mid-plane (i.e. 4^{th} layer for specimen1, 6^{th} layer for specimen6 and 9^{th} layer for specimen7) are vibrated for various frequency and data's is recorded.

Fig.4. (a) shows specimen6 giving a maximum voltage of 1.849V at its resonant frequency of 10 Hz. specimen1 gives a maximum voltage of 1.835V a decrease of 0.76% from specimen6 at it resonance frequency of 8 Hz. Specimen7 gives a maximum voltage of 1.609V a decrease of 12.31% from specimen1 at its resonance frequency of 7 Hz. These data show that as the thickness increases there is a marginal decrease in voltage generation but along with that also there is a decrease in the resonance frequency with the increase in the thickness.

4.2. Effect of position of PFC-W14 embedded in a multilayer composite on voltage generation

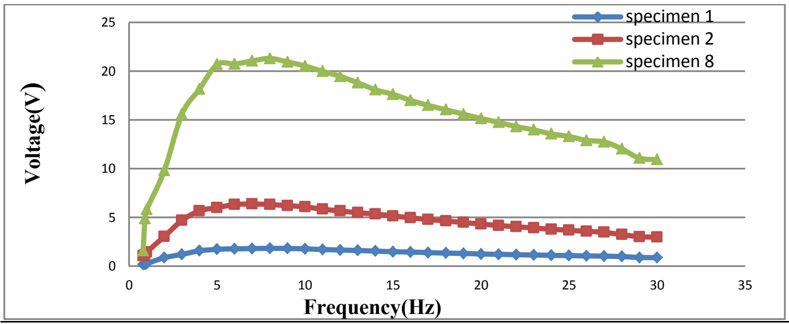

Fig.4. (b) Comparison Based on Position

Specimens1, 2& 3 are of thickness 1.5mm with PFC-W14 embedded at different positions. In specimen1&2 PFC-W14 are embedded at 0.6mm and 0.9mm from bottom respectively and in specimen8 PFC-W14 is pasted over its outermost surface using epoxy resin. Specimen1 generates a maximum voltage of 1.835V at its resonance frequency of 8Hz which increases by 245.67% (6.38V) in specimen 2 and a phenomenal increase of 1061.3% (21.31V) in specimen8 at same resonance frequency.

4.3. Effect of connecting two PFC-W14 parallel and laid adjacent to each other in same layer

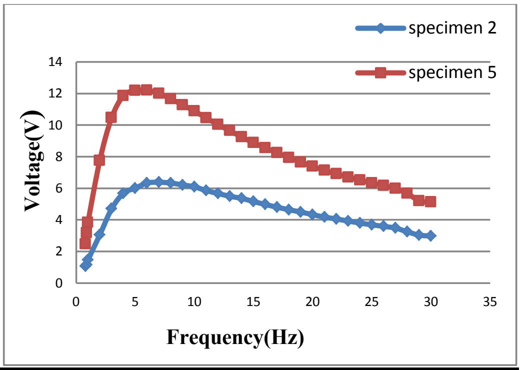

Fig.4. (c)
Comparison of voltage generation of specimen 2 and 5

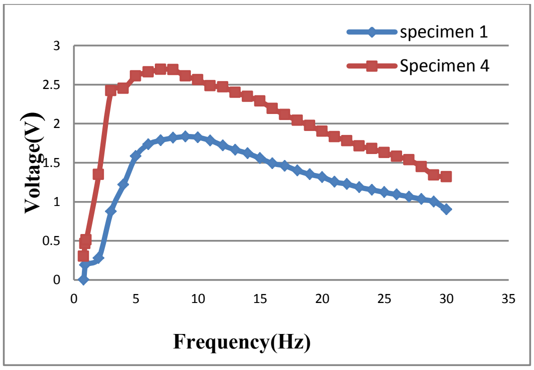

Fig.4. (d)
Comparison of voltage generation of specimen1 and 4.

Fig.4.(d) shows that there is an increase of 46.81% when two PFC-W14 are parallely connected to each other and are embedded at central layer when compared to specimen1 and Fig.4. (c) shows that there is an increase of 91.37% in voltage generation when 2 PFC-W14 are parallelly connected to each other at a distance 0.9mm from the bottom when compared with specimen 2. In specimen5& 4 two PFC-W14 at same layer has been embedded and it was observed that resonance frequency was lowered from 7 to 6 Hz and 8 to 7 Hz respectively. This clearly shows that even if multi PFC-W14 is connected parallely to increase voltage generation it has to be at higher level as much near the surface or at the top of the surface to get maximum voltage increase which also leads to the decrease in the resonant frequency of the specimen.

4.4. Effect of embedding 2 PFC-W14 at different layers rather than in same layer adjacent to each other and connected parallel.

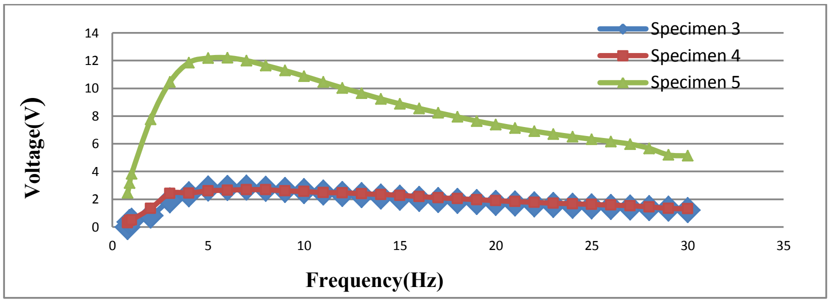

Fig.4. (e) Comparison Based On 3-4-5

Fig.4. (e) shows that voltage generation of specimen3 of thickness 1.5mm with 2 PFC-W14 embedded at 0.3mm and 0.9mm from bottom are connected parallel which generates a maximum voltage of 2.827V which is a sharp drop by 76.84% when compared with specimen5. Comparing specimen3 and specimen 4 there is a very marginal increase of 4.93% of maximum voltage generation in specimen 3 as compared to specimen 4 .these results shows that it is better to embed multi PFC at same layer and connect parallel rather at different layers and then connect it parallel.

5. Conclusions

This experiment shows that with increase in thickness the voltage generation decreased along with that resonant frequency at which maximum voltage is generated for a particular thickness showed a decrease which is clear from Fig.4. (a). Fig.4. (b) shows that the voltage generation kept on increasing from centre to the top. At the top most there was an increase of voltage generation by about 1061% from 1.835V to 21.31V. It should be noted that big civilian aircraft's cockpit works on a 28V battery. Specimen8 fabricated for this paper was able to generate a maximum voltage of 21.31V for a moderate frequency of 8 Hz. If PFC-W14 are pasted on the tip of wings of a UAV it will help in increasing its range by recharging of UAV's battery in air itself. Bigger aircrafts also on engine failures can use the power generated due to wing loads on the leading edge for working of vital instruments in the cockpit which will help pilots during emergency landings.

Results from Fig.4. (d) and Fig.4. (c) show that voltage generation can be further increased by keeping multiPFC-W14 in same layer adjacent to each other and connected parallel. Fig.4. (d) shows that there is an increase of 46.81 percent when two PFC-W14 were used instead of one at centre ie after 6^{th} layer from bottom. Fig.4. (c) shows that there is an increase of 91% when two PFC-W14 were used instead of one at a distance of 0.9mm from the bottom an increase by two times from Fig.4. (d). So positioning of multi PFC-W14 nearest to surface is important for most efficient increase in voltage generation. Fig.4. (e) shows that voltage generation of specimen3 of thickness 1.5mm with 2 PFC-W14 embedded at 0.3mm and 0.9mm from bottom are connected parallel which generates a maximum voltage of 2.827V which is a sharp drop by 76.84% when compared with specimen5. Comparing specimen3 and specimen 4 there is a very marginal increase of 4.93% of maximum voltage generation in specimen 3 as compared to specimen 4 .these results shows that it is better to embed multi PFC at same layer and connect parallel rather at different layers and then connect it parallel.

6. Appendix A

Table 1 - Specimen Specifications

	Specimen1	Specimen2	Specimen3	Specimen4	Specimen5	Specimen6	Specimen7	Specimen8
Length(mm)	142	142	142	142	142	142	142	142
Width Top(mm)	74	74	74	98	98	74	74	74
Width Bottom(mm)	34	34	34	58	58	34	34	34
Total Thickness	1.5	1.5	1.5	1.5	1.5	1.1	2.1	1.5
Thickness of '1' Glass fibre layer	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
No: of Glass fibre layers	12	12	9	12	12	8	18	12
Thickness of Piezofibre	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
No: of Piezofibres	1	1	2	2	2	1	1	1
Position of Piezofibre	Center	At a height of 0.9mm from Bottom	At a distance of 0.3mm and 0.9mm from bottom	Placed Adjacent to each other at Center	Placed Adjacent to each other at a height of 0.9mm from Bottom	Center	Center	At the Surface of the composite

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