A review of application of Piezo-resistive nature of Carbon fiber based Concrete for development of Strain measuring Smart Structures

[1]Yash Dhadke, [2]Neel Sanghvi, [3]Adeshri Chavan, [4]Shashikant Auti

[1]UG Student, [2]UG Student, [3]UG Student, [4]Assist. Professor

[1]Mechanical Engineering Department,

[1]DJ Sanghvi College of Engineering, Mumbai, India.

Abstract: This paper talks about the concept of using the Piezo-resistive properties of Carbon fiber reinforced concrete, which behaves as an intrinsically smart concrete. Behavior of steel fiber reinforced and carbon fiber reinforced concrete is discussed in short. The core ingredients and additives used in Carbon fiber reinforced smart concrete are discussed in detail. Then the mechanism of Piezo-resistivity in the material is explained. The process of preparing the concrete, the various aspects involved, the Wenner four pin method is explained. The authors then propose some prospective applications which make use of the given material. Despite invention in 1992, this material is not being commercially used. Possible reasons for this are described. Conclusion and References follow.

Index Terms - **carbon fibers, smart concrete, piezo-resistivity, carbon fiber reinforced concrete.**

I. INTRODUCTION

This paper reviews the process of development of carbon fiber based smart concrete which behaves like a highly sensitive strain gauge. A paper by Chung et al in 1993 [1] was the first academic publication investigating intrinsically smart concrete, works prior to that talking about extrinsically smart concrete. Addition of carbon fibres helps in monitoring the hidden stresses inside the concrete and finding trouble in the structure long before the crack is visible to the human eye. The goal of the large number of experiments that have been undertaken in this area since the early 1990's is to develop a concrete based building material in place of standard commercial concrete that can act as a sensitive strain gauge thus being able to sense the load acting on a structure made out of it, thus being able to monitor structural health and detect abnormal loading conditions by a non-destructive process [2] [3]. Multiple strain sensing devices of this kind can be used in tandem with a simple computer based control system to continuously monitor the stresses acting at various locations in the building's or the structure's framework, thus being able to take immediate action in case of development of abnormal or life threatening situations. This system will be highly cost effective and will be ideal for small structures where continuous monitoring of structural health is important.

Abbreviations – Carbon Fibers (CF), Carbon Fiber reinforced Concrete (CFRC), Methylcellulose (MeCe), silica fumes (SF), Napthalenesulfonic acid (NaSuAc), Polyacronitrile (PAN).

II. PROCESS DESCRIPTION

This method uses *Piezo resistivity* (first discovered by Lord Kelvin in (1856) [4] which is the scientific term used for the phenomenon in which there is a change in the electrical resistivity of a material (metal, semiconductor or other) when a mechanical strain is applied on it. The composite is manufactured by addition of carbon fibers or steel fibers. Steel fibers have been studied for developing intrinsically smart concrete [5]. Steel fiber based systems exhibit lower signal-to-noise ratios but show poor reversibility on unloading, compared to carbon fiber based systems [6] [7]. Both these factors are important when these systems are scaled up from an experimental to an industrial or commercial level and these may be potential factors for why even carbon fiber systems have not been applied to commercial and residential buildings. The electrical resistivity changes in response to damage or deformation, and that is what makes smart concrete a sensor.

III. MATERIAL AND COMPOSITION

The primary ingredients of the carbon fiber strain sensing smart concrete in various experiments have been the following: 1. Sand 2. Water 3. Cement 4. Carbon fibers. The supplementary additives follow afterwards.

3.1 Core materials:

a) Sand: It functions as an aggregate in the obtained concrete. It occupies a large volume by proportion, thus adding body to the composite. It is the material that the cement and water paste coat and bind together. Historically, aggregates used have varied between sand, crushed rock, and other natural stones like basalt, granite, marble. The main factor which limits the size of the aggregate used is the depth of the concrete slab required. The maximum size for aggregate allowed is one-third of the required slab thickness [8]. None of the experiments conducted until now, have used aggregate other than sand which leads to scarcity of data regarding the behavior of carbon fiber based smart concrete having other materials as

aggregate. This may be one of the main reasons which hinder the commercialization of this kind of intrinsically smart concrete.

b) Water: Water binds the mass of Portland cement and aggregate into a hard, compact and crystalline mass. This happens by means of a set of chemical reactions which occur simultaneously. The reactions occurring are the following: A. Hydration of Tricalcium Aluminate. B. Gel formation of Tetra-calcium Aluminoferrite. C. Tobermorite gel is formed due to hydration of Dicalcium and Tricalcium silicates. This gel is 50% of hydrated cement by volume. D. Crystallization of Calcium hydroxide and Tricalcium Aluminate. The strength of the cement is determined by amount of gel formed and the extent of crystallization [9]. Hence it can be said that water is a key component to the process of converting the raw materials into a concrete structure

c) Cement: It acts as the base material of the concrete. The major constituents are Lime, Silica, and Alumina. The secondary constituents are Iron oxide, Magnesium oxide, and Sulphur Trioxide and Alkali oxides [10].

d) Carbon fibres: Addition of calculated volumes of Carbon fibers results in improvement of mechanical properties of concrete obtained. This was verified by Chung et al in 1992 [11] when experiments conducted showed that addition of 0.5% by weight of short pitch-based carbon fibers to plain concrete improved costs by 39%, but yielded a flexural strength increase and compressive strength increase of 85% and 22% respectively [11]. Conventionally, PAN based Carbon fibers have been used to manufacture CFRC composites. In this case, a major drawback was high cost [12]. The development of Pitch based Carbon fibers helps to overcome this problem. Both the kind of fibers show the same extent of reinforcement. For experimentation, pitch based fibers are preferred due to their lower cost.

3.2 Admixtures: The experiments which have been performed in the relevant area, all have used admixtures; these are chemical substances added to the concrete mixtures immediately before or during mixing [refer Table 1]. These primarily perform the following functions: 1.Reduce construction cost 2.To modify the properties of the hardened concrete 3.Ensure quality of the Concrete mixture during mixing, transporting, placing and curing. The admixtures which have been used in the conducted experiments are:

a) Napthalenesulfonic acid: It is a water reducing admixture. It reduces the amount of water required for the concrete to set by 5 - 10 %. It was reported by Chung et.al [1] that when carbon fibers are added to the concrete paste, the slump of the material decreases (i.e.) the workability of the material decreases. This phenomenon can be compensated by decreasing the amount of water added to the cement-aggregate mixture, the effect of which is balanced by addition of Naphthalene-sulfonic acid.

b) Dispersion agent: Addition of this substance enhances the dispersion of Carbon fibers in the concrete. These can be methylcellulose, silica fume or latex. Addition of Latex decreases the change in resistivity. Chung et.al reports that Methylcellulose acts as the best Dispersion agent as the resistivity change begins to occur as soon as the stresses are applied. In case of Silica Fume and Latex, the resistivity changes begin to occur only after a certain amount of stresses have been applied. The same effect is observed when the only Latex is used as the dispersion agent.

Table 3.1 : Summary of parameters of various Experiment conducted with CFRC

Article reference	Specimen Size	Curing Time	Carbon fiber %	Additives used
2	50 mm cube, 70 mm cube	7/14/28 days	0.24 by cement volume	MeCe, SF
1	2 inch cube	7 days	0.2-0.4 by cement weight	1.No additive 2.Latex 3.MeCe 4.MeCe & SF
16	2 inch cube, Dog bone specimen for tensile test	7 days	0.5 by cement volume	1.NaSuAc, Latex, MeCe

IV. MECHANISM OF PIEZORESISTIVITY FOR CFRC

Piezo-resistivity mechanism takes place in two steps for the reversible (elastic) processes: 1) the fiber pull-out is activated by straining and accompanies crack opening 2) the reverse, fiber push-in, accompanies crack closing. As the fiber pull-out is quite negligible as compared to the length of the fibers, the structure (fiber-matrix interface) is essentially not affected by straining. Although the contact between the fibers and the matrix increases due to the fiber pull out, which in turn increases the resistivity of the whole structure in question [13].Therefore the length and the orientation of carbon fiber also affects the piezo-resistivity. The mechanism works only when the carbon fibers are well dispersed in the concrete matrix for which the above mentioned additives (i.e. methylcellulose) is used. The diameter of the carbon fiber should be less than the crack opening in order to be more conducting than the matrix and cause the reversible stress sensing possible. The reversibility of the piezo-resistivity is possible due to the fact that the carbon fiber bridges the gap on crack opening [14]. Table 4.1 shows the linear increase of resistivity of mortar with the increase in strain.

TABLE 4.1: Gradual change in mortar due to addition of CF

Strain	Electrical Resistivity for Plain Mortar (10^6 ohm-cm)	Change	Electrical Resistivity for Mortar containing MeCe and 0.24% vol. CF (10^4 ohm-cm)	Change
0.00	1	0	4	0
0.00025	1	0	4	0
0.0005	1	0	6	$+2*10^4$
0.00075	1	0	10	$+4*10^4$
0.001	1	0	18	$+8*10^4$
0.00125	1	0	25	$+7*10^4$
0.0015	1	0	32	$+7*10^4$
0.00175	3	$+2*10^6$	38	$+6*10^4$
0.002	13	$+10*10^6$	17	$-21*10^4$

V. EXPERIMENTATION

The various experiments that have been conducted, all have used the Wenner four probe (four pin) method to measure the resistivity of the CFRC material "Fig 1". None of the experiments have used the Schlumberger method. It is known that the Schlumberger method mandates the use of highly sensitive voltmeters compared to the Wenner method [15]. The Wenner four pin method is simple in terms of equipment required and execution. The process and its application to concrete has been explained in [2] and [27]. Electrical contacts were made by applying silver paint to the specimens. The volume resistivity was measured by Four Probe Method [19]. Copper wires are wound around the layers and these were connected to the R.P.S, voltmeter and ammeter. The middle two copper wires from cube are connected to two probes of the voltmeter. The positive end of ammeter is connected to positive end of R.P.S and negative end of R.P.S was connected to one end of the cube. The negative of the ammeter was connected to another end of the cube. This is the four probe method of measuring resistance. From the voltage and the current values obtained at each stage of loading, the resistance is calculated. The outer two contacts give the current value ammeter and the middle two contacts in voltmeter give the voltage. Resistance is computed using Ohm's law. This method enables the measurement of the volume resistance even in presence of a non-zero contact resistance, thus it gives us accurate volume resistivity measurement [20].

Fig.1 Schematic diagram of four probe method
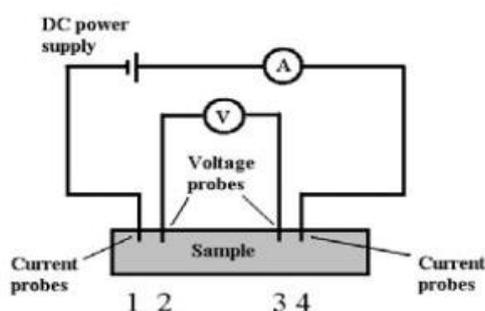
VI. STRUCTURAL HEALTH MONITORING

Bridges, buildings and many other structures are prone to deficiencies due to different loading and environmental conditions such as corrosion, material aging, fatigue and the coupling effects with long-term and extreme loads. These structures, when damaged or deteriorated, no longer meet the required standards and need to be repaired and rehabilitated or even rebuilt. In order to detect any flaws in the structures performance before any serious loss of capacity occurs, a technology known as Structural Health Monitoring (SHM) is used. By means of these devices and a systematic procedure, SHM is able to determine the existence of any damage, locate it and estimate its magnitude. Subsequently, appropriate repair and rehabilitation of the structure can take place in a timely manner, preventing any catastrophic failure and increase in the maintenance cost.

CFRC sensors with the necessary four probe circuits can be installed in the major columns to continuously monitor the stresses acting on them so that the building can be vacated when the strain in the sensor exceeds a given value. The calibration process is complex and will require a thorough understanding of the loads and stresses that will act on a given structure, with regards to magnitude, direction and nature.

The same concept can be applied to bridges; conventional, cable stayed, and modern suspension types. A structural integrity monitoring system for low risk environments can be developed which will be a cost effective alternative to conventional Structural Health monitoring systems which are implemented in buildings like Burj Khalifa, Shanghai WFC and bridges like the Tsing Ma and Ting Kau bridges fegsin Hong Kong. Unlike SHM systems, the proposed system will make use of CFRC sensors and there will be no data storage. Data processing will be real time. Tailored software programs can be used to compute the state of the structure as Safe or Unsafe and necessary steps can be taken by the authorities. This aspect is further explained in section VII.

Strain-Resistivity response of the CFRC stress sensor and that of a hypothetical plain concrete sensor can be summarized in the given table. It can be concluded that a CFRC stress sensor is more sensitive and gives a more uniform response compared to a hypothetical plain concrete sensor.

VII. ENHANCEMENT OF SENSOR SENSITIVITY

$$\text{We know: } \text{Stress} = \frac{\text{Force}}{\text{Area}}$$

In a given situation the given values of Change in Force and the area may not produce an adequate change in stress. The inadequate value may not produce requisite change in the four probe current values. To enhance the sensitivity of the sensor, the cross sectional area of the sensor in the plane perpendicular to axis of application of force must be decreased. This will result in higher change in stress for a given change in force.

$$\Delta\text{Stress1} = \frac{\Delta\text{Force}}{\text{Area1}}$$

$$\Delta\text{Stress2} = \frac{\Delta\text{Force}}{\text{Area2}}$$

When area 2 is decreased, the value of ΔStress2 will increase.

The given image is a representation of the proposed sensor with the attached four probe attachments. The cross section of the sensor will be square or circular in shape. The tensile or compressive forces will act perpendicular to the end faces
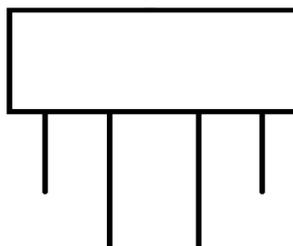
VIII. POTENTIAL APPLICATIONS

- *Systems for intruder detection:* Deborah Chung points out in a University of Buffalo article [21] that this technology can be used for intruder detection. The authors propose that in sensitive areas, a continuous patch of CFRC can be built on the land surface which is a few millimeters thick and approximately 8 feet wide. Four probe method measurement circuits can be installed and the required electronic circuitry can be laid up to the nearest security checkpoint. This system would make it impossible for any potential intruders on foot, or in a vehicle to cross the border under consideration. This system can be applied to airports, sensitive international borders, government laboratories.

- *Monitoring health of a structure:* The immediate advantage of using CFRC to build certain parts of a structure is that continuous stress monitoring can be done. Skyscrapers built in coastal areas can be monitored for their structural health under the effect of Strong winds that act on them during Typhoons & Hurricanes. Buildings in earthquake prone areas can be monitored for their structural health by installing CFRC parts in their foundation as well as the main structure. This can be done especially in the buildings built around those fault lines which show a history of seismic activity (e.g.) Hayward Fault zone in the San Francisco bay area, San Andreas Fault in California, USA [22]. Similarly, CFRC components can be installed in bridges to monitor the health of the frame of the bridge. Excessively unsafe amounts of traffic and effects of high speed winds can be effectively realized. Steps can be taken to decrease the number of vehicles passing and to vacate the bridge when the unsafe stresses act due to high speed winds.

- *Continuous Data harvesting for Research*: This system of CFRC and requisite electronic systems can be used to acquire data that can be used for research in the fields of building materials, structural design, building planning and architecture [23] and transportation engineering [24]. CFRC components can be placed in/at the critical members/joints of the structure to monitor stresses. This data after systematic analysis can give significant information in various aspects like the time of peak occupancy, the part of the structure having the maximum occupancy, parts of the structure susceptible to maximum damage and so on.

- *No – parking Vigilance*: The CFRC system can be used to develop an effective solution to prevent people from parking vehicles were doing so is prohibited (e.g.) Cycle tracks, Sidewalks, Promenades, etc. Parking a vehicle can be caused to trigger a loud, irritating alarm will signal people to park their vehicles in appropriate places.

IX. BARRIERS TO COMMERCIALISATION

A) Lack of Data Regarding CFRC

A piezo resistive material is a material in electrical resistivity in a given direction is directly proportional to mechanical strain applied in that direction. The basic concept states that when the mechanical stresses are caused in the material, changes occur in the inter-atomic spacing which affects the bandgaps, making it easier or difficult for the given material to conduct electricity. For a certain range of strain values, we can define a constant known as Piezo resistive coefficient which we can mathematically express as:

Piezo resistive coefficient (σ_k) = (Change in resistivity per unit original resistivity) / Strain applied (ε)

At present, many commercial pressure sensors employ the use of piezo resistive properties of Germanium, Polycrystalline Silicon, and Single crystal silicon. There is plenty of data available in the public domain regarding the material properties regarding the simulation of such piezo resistive materials. But there is no data available about the properties of Carbon fiber reinforced concrete. This is the primary factor which hinders the development of CFBSC sensors and consequent design of structural health monitoring solutions based on these sensors.

B) Other Barriers

- Deborah Chung mentions in an article that use of CFRC structures would increase construction costs about 30% over the current construction costs. For commercial purposes it is not feasible. Although use of CFRC only in the main joints and columns of a structure can possibly overcome this barrier.
- Development of the required electronic systems to implement the four pin method for each CFRC structure used in a given system (building, etc.), is a complex task. Also the maintenance of such electronics is a demanding task and increases costs in the form of consultation fees, material costs, maintenance services.
- The signal to noise to ratio must be maintained very low to justify the implementation of CFRC systems, which requires robust design processes.
- The application of CFRC in the applications proposed in section 6 will demand the application of integrated software and hardware platforms like SCADA. The initial financial investment and yearly running costs for such systems are often very high and thus may not clear Government and Corporate scrutiny.
- All the experiments conducted on CFRC are conducted using sand as an aggregate in cement. No experiments have been conducted while taking gravel as an aggregate. In practical use (i.e. while making a bridge pier) gravel is used to impart strength. Lack of research on CFRC with gravel as an aggregate, makes commercialization of CFRC a very distant goal.

- Different curing period required for concrete with dissimilar amount of carbon fiber makes the process more sensitive to handle. In case of concrete the mixing and curing process is quite simple and routine, whereas in CFRC due to the addition of carbon fibers the whole process requires expertise.

X. CONCLUSION

Carbon fiber reinforced smart concrete is a piezo resistive material which can be used as a highly sensitive strain gauge when the appropriate circuitry is applied. In this paper, after the necessary introduction regarding the material and its constituents, a brief review of the experimentation technique follows. Mechanism of Piezo resistivity is also described. Potential space are proposed and described. Probable barriers to commercialization are explained. It is concluded that this material holds tremendous potential for use as a strain measuring device, thus for use in multiple situations.

XI. REFERENCES

[1] Pu-Woei Chen and DDL Chung 1993 Smart Mater. Struct. 2 22
[2] S. Sathyanarayanan, K & Sridharan, N. (2016). Self-Sensing Concrete using Carbon Fiber for Health Monitoring of Structures under Static loading. Indian Journal of Science and Technology.
[3] AIMS Materials Science, 3.2.357.379, 2016-03-14, Sohel Rana, Subramani P, Raul Fangueiro, Antonio Gomes Correia, matersci-03-00357.
[4] Proc IEEE Inst Electr Electron Eng. 2009; 97(3):552.
[5] D.D.L Chung Journal of Intelligent Material Systems   and Structures.
[6] Bayasi, Z & Kaiser, H. (2001). Steel fibers as crack arrestors in concrete. Indian Concrete Journal. 75. 215-222.
[7] Ali Alavizadeh-Farhang and Johan Silfwerbrand Transportation Research Record: Journal of the Transportation Research Board 2000 1740: 25-32
[8] Literature from the Concrete Countertop Institute
[9] Material released by Civil Engineering Department, Eastern Mediterranean University
[10] Documentation released by Portland Cement Association
[11] Pu Woei Chen, D.D.L Chung Composites, 1993, Volume 24, Number 1, 33-48
[12] Xiaosong Huang Materials 2009, 2, 2369-2403.
[13] Liqing Zhang et al 2017 Mater. Res. Express **4** 125704
[14] Sihai Wen and D.D.L. Chung Advances in Cement Research 2003 15:3, 119-128
[15] Literature obtained from Dr. Pamela Burnley, University of Nevada, and Las Vegas
[16] Pu Woei Chen, D.D.L Chung J. Am. Ceram. Soc. 78-[3]-816 18-1995
[17] NPCA Article: Concrete – Evolved 15 Nov 2016
[18] Wen, S., & Chung, D. D. L. (2007). Piezoresistivity-based strain sensing in carbon fiber-reinforced cement. ACI Materials Journal, 104(2), 171-179
[19] Shi, Zeng-Qiang & Chung, Deborah. (1999). Cement and Concrete Research. 29 435-439.
[20] Singh, Yadunath. (2013). Int. Journal of Modern Physics Conference Series. 22. 745-756.
[21] John Della Contrada, UB News Centre, 22 Sep 2005
[22] Documentation released by the UC Berkeley Seismology Laboratory
[23] D Walker A bottom-up approach to better buildings 28 March 2018 terrapinbrightgreen.com
[24] R Ayers Five ways the Data is assisting the construction & civil engineering industry 19 July 2018 Dataconomy.com
[25] http://www.theconcreteportal.com/cons_rel.html
[26] "Stress-strain behavior of confined normal grade concrete" - Kalluru .Rajasekhar1, M.Praveen Kumar. Int. Journal of professional Engineering Studies, Vol VIII, Issue 3, Mar 2017
[27] Pejman Azarsa and Rishi Gupta, "Electrical Resistivity of Concrete for Durability Evaluation: A Review," Advances in Materials Science and Engineering, vol. 2017, Article ID 8453095, 30 pages, 2017.