Evaluating Self-sensing Property of Carbon Fibre Cement Composite by experimental study and Finite Element Modelling For Structural Health Monitoring Applications

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Abstract. Structural health monitoring (SHM) is a novel area of research and it is the process of implementing a damage detection strategy. The initial step of implementation a SHM system involves, incorporating structural self-sensing capability of material to achieve the reliability and possesses long term stability. Smart sensing technologies involves the applications of fiber optic sensors and self-diagnosing fiber reinforced composites which possess important capabilities of monitoring various physical or chemical parameters to achieve the durable service life of structures. The addition Carbon fiber to concrete composites possess the electric properties, therefore it can be used as Smart sensing composite that provide the capability of non-destructive flaw detection in structures. In this paper, carbon fiber (CF’s) is added to cement composite to attain piezoresistive properties of composite. This carbon fiber is added in the composite by forming tube which act as conductive element. Later on, electromagnetic test is conducted to this sensor by embedded into structural elements that is in beam and column to evaluate self-sensing properties. Scanning electron microscope is carried to understand the morphology of sample. A Finite elemental modeling is done to validate this experimental result. A FEA modelling is carried out using ANSYS software, subjected to steady steady static loading and electric analysis were done. Form the experimental is observed that addition carbon fiber induces conductivity property and the resistance decrease for failure load. The resistivity from experimental study observed is 9.2 kilo ohms and 11.2 kilo ohms for embedded carbon fibre sensor into beam and column respectively. The percentage error in electrical analysis of experimental tests compared with analytical modelling, found to be 15 %. Based on these results it can be concluded that carbon fiber cement composites have great potential and they can be used for structural health monitoring applications.

Keyword: Carbon fibre Composite Sensor, Electrical properties, Self-Sensing Material, ANSYS Modelling

1. Introduction
Self-sensing smart composites are becoming popular in recent years as they can increase the safety and performance of civil engineering structures/infrastructures. These self-sensing smart composites have ability to measure the change in their electrical resistivity with applied stress and strain hence this distinctive property make them useful for structural health monitoring applications. The self-sensing property is defined by the material which possess the ability to sense on its own when it is subjected external factors such as stress, strain, temperatures and corrosion etc. Since the self-sensing composite have ability to shows detectable change in their electrical resistivity with applied stress or strain, therefore they can detect deformation and damages on its own. Self-sensing composite works based on piezo resistivity principle. The piezo resistivity property in composites is achieved through addition of conductive materials. From last decade various type of conductive materials are available such as carbon fibres (CFs), carbon particles as well as carbon nanomaterials such as carbon nanofibers (CNFs) and nanotubes (CNTs). These conductive materials form a conducting electrical network within the composites makes them smart self-sensing composites for structural health monitoring applications [1-5]. Few studies have shown that percolation threshold of Carbon fibre is between 0.5 and 1.0 vol.% of the cement paste for self-sensing ability [9-10]. In this context, the present paper deals development and analysis of self-sensing carbon fibre cement composite embedded sensor for
the health monitoring purpose. This carbon fibre is added in the composite by forming tube which act as conductive element. Later on, electro-mechanical test is conducted to this sensor by embedded into structural elements that is in beam and column to evaluate self-sensing properties. These composites designed as self-sensing so that they can perform both strengthening and health monitoring functions. This leads to elimination of installation of electrical sensors from outside for health monitoring of structures.

2. Experimental Investigation

2.1. Materials Used
Carbon fibre is about 5-10 micrometres and is mostly composed of carbon atoms. Carbon fibre has several advantages such as high stiffness, high tensile strength, high temperature tolerance, low weight, high thermal expansion etc. Properties of carbon fibre is listed as in the Table 1. used for the current work. Since the copper wire has high electrical conductivity property hence it is used as electrode. Ordinary portal and cement and Zone II sand with water cement ration of 0.45 is used for the preparation of sample.

| Table 1. Properties of carbon fiber |
|-----------------------------------|
| Length of fiber | <5mm |
| Diameter of fiber | 8μm |
| Density of fiber | 1.8g/cc |
| Tensile strength | 3500 N/mm² |
| Tensile modulus | 283x10³ N/mm² |
| Poisson’s ratio | 0.25 |

2.2. Preparation of sample
A cement composite sample of 80mm x 80mm x 50mm with hallow tube having diameter of 10mm filled up with carbon fibre was prepared shown in Figure 1. In the beginning mixing of material and moulding is done, once concrete sets hollow tube is filled carbon fiber is of length of 2mm and copper wire of having 1.6mm diameter is inserted in the tubes which act as electrode. The moulds were kept for 24 hours. After 24 hours demolding was done. The de-moulded specimens were kept for curing for 28 days and after that curing specimens were tested. The column and beam is casted as per standard dimension 150x150x500 mm. Once the concrete mix is poured till half of the mould then the carbon fibre composite sensor is embedded and fully filled up with a concrete in the mould. After the 28 days of curing, testing of structural elements are carried out.

![Figure 1. Preparation of Carbon fiber composite Cement based sensors](image-url)
2.3. Electromechanical test on sensor and structural elements

Electromechanical test conducted on cement-based carbon composite sensors with the applied compression load. The experimental is setup as shown in figure 2. The change of electric resistance measured using digital multimeter Agilent 34401A and UTM machine of the capacity of 10 ton is used to apply the load on sensors. The change of electric resistance measured against the applied load simultaneously to get the so that variation of electric resistance. Electromechanical test is carried out for structural components on beam and column shown in Fig. 4. Both bending and compression loading is applied by UTM of 100-ton capacity and Resistance is measured using digital multimeter Agilent 34401A [23].

![Figure 2. Compression test on sensor](image1)

![Figure 3. Compression test on column embedding sensor](image2)

3. Result and discussion

3.1. Electromechanical test on the sensor

Electromechanical test using two probe method subjected to Compression load test were conducted on the cement-based Tube sensors as per ASTM C-109. The results are as shown in figure 4.

![Figure 4. Load and deflection (a) and Variation of Load and resistivity (b) of Carbon fibre sensor subjected to compression](image3)
From figure 4, we can see that the deflection of Tube sensor is 3.55mm and maximum load is 94.44 kN. when carbon fiber is added to the cement paste the load carrying capacity of the specimen increases. This is due to as carbon fiber has high stiffness, strongest materials among the nanoparticles and it is widely used because of their strong interfacial interactions and excellent stress transfer properties. When loading was applied to the Beam it was observed that the Resistance was increasing with increasing in load because when load was applied the electrical networks which was found due to the presence of carbon Fiber. There was increase in resistance on further increase in load again there will be increase in resistance because since in Flexural load set up the Cement based Sensors will be directly below the application of load. The resistance found to be 3.3 kiloohms for failure load.

3.2. Electromechanical test on structural components
Electromechanical test is performed to measure sensitivity of the sensor to the load after embedding into structural components. The tests are conducted on structural element as shown in figure 3 that is on beam and column by embedding cement-based carbon composite sensor into it. The bending and compression load is applied on these components using UTM of 100-ton capacity. Figure 5 represents variation of electrical resistance with respect to application load for beam and column. From test results it indicates that sensors in structural components shows variation in strain sensitivity with respective to the load by varying electric resistance. It is observed that variation in electrical resistivity of structural components is same as that of electromechanical test on sensors, so from these results it can proves that structural components can make self-sensing by embedding carbon fiber composite into it[23].

![Figure 5. Variation of Load and resistivity of beam (a) and column(b) embedded carbon fibre sensor subjected to flexural and compression loading](image)

3.3. Microstructural Analysis
Scanning electron microscopy analysis is carried out to know the surface topology and morphology of sample. From the figure 6, its observed that dense formation of the matrix is due to the addition of carbon fiber into cement matrix as Portland cement is a porous material, addition of carbon fiber will fill up these pores hence the strength of matrix increased. The Figure also indicates Carbon fibres in sample and their larger diameter can efficiently bridge the larger scale pores, hence theses carbon fibre forms conducting network leading to measure a change in the electrical resistance when it is subjected to loading.
4. Finite Element Modelling

Finite Element Analysis (FEA) is a numerical analysis method widely used for the analysis of structures to get the precise prediction of the component's response subjected to various structural loads. To study the behaviour of concrete, FEA has been the preferred method over the decades as it provides reliable and faster than the experimental method, hence it has become possible to model the complex behaviour of reinforced concrete structures. In finite element analysis, structural element is divided into smaller parts and then simulates static loading conditions to evaluate the response of concrete. The use of this technique is increasing because of enormous advancement of engineering and computer knowledge. In this proposed work, mechanical properties and electrical analysis carried for the carbon fibre cement composite sensor and structural element such as beam and column are embedded with this sensor. Analysis has been done using ANSYS software. The beam and column are analysed for total deformation, equivalent stress, equivalent elastic strain and thermal variation. Comparison has been made between experimental study and ANSYS modelling carbon fibre and results are analysed.

4.1. Material Properties

For the present work, ANSYS 19.2 version software is used for modelling and Analysis. Engineering data is considered as one of the most important and basic requirements of the ANSYS Software. In this work, we add the required materials from the ANSYS library. The materials in it are either preloaded or we can add different materials and modify them according to our requirement. Following tables shows the various properties of materials used for modelling and analysis purpose.

Table 2. Material Properties of Carbon Fiber

| Properties                                 | Values             |
|--------------------------------------------|--------------------|
| Density                                    | 1.518E-09 kg/m³    |
| Young’s Modulus X direction                | 1.233E+08 MPa      |
| Young’s Modulus Y and Z direction          | 7.78E+06 MPa       |
| Poisson’s ratio in XY and YZ               | 0.27               |
| Poisson’s ratio in XZ                      | 0.42               |
| Shear Modulus in XY and YZ                 | 5E+06              |
| Shear Modulus in XZ                        | 3.08E+06           |
| Thermal Conductivity in X direction        | 2.5 W/m. K         |
| Thermal Conductivity in Y and Z direction  | 0.55 W/m. K        |
Table 3. Material Properties of Concrete

| Properties                        | Values        |
|-----------------------------------|---------------|
| Density                           | 2400 kg/m³   |
| Young’s Modulus                   | 27.38 MPa    |
| Poisson’s ratio                   | 0.3         |
| Tensile ultimate strength         | 4.5 MPa      |
| Tensile Compressive strength      | 30 MPa       |
| Isotropic thermal Conductivity    | 2.5 W/m. K   |
| Specific Heat                     | 1055 J/kg.K  |

4.2. Modelling

Modelling is done by geometry tool and preparing the exact replica of the real structure. While preparing model designer has the freedom to choose the plane and construct the structure. It contains mainly two parts, sketching and modelling. Sketching involves the providing shapes and fix the dimensions, where as in modelling helps in coordinate of different planes. Geometrical size and shape of sensor 80 x 80 x 50mm is modelled and create three hollow tubes having a diameter 10mm is created in the model and then copper wire of 2mm diameter is inserted inside the tubes. In meshing, rectangle elemental size assigned as 2mm for cement composite and for carbon sensor tube elemental size assigned CFX of 0.5mm. In a similar way modelling of beam and column of size 150 x 150 x 700mm is done by inserting this composite. A steady state analysis carried out subjected to flexural and compression loading for beam and column respectively. A failure load applied which is obtained from experimental result to get the validate the ANSYS modelling.

4.3. Electrical Analysis

In a composited electrical resistance measured by various ways. If the current contacts are on the same surface in the plane of the composite, the current penetration is in the surface region only. Fiber breakage indicated by measuring the resistance in the plane of composites. In a similar way when the current are on edge of the composite or located in the hole that goes through the thickness of the composites, the current penetrates through the entire cross-section of the composites. when current flows through the thickness it represents damage, therefore penetration of current through the entire cross-section is suitable for resistance measurement for detecting damage in composites. In ANSYS, the current density in the form of voltage is given to specimen for failure load obtained by experimental load and resistance measured as below ohm’s formula.

\[ R = \frac{V}{I} \]  

Where, R= Resistance in Ohms  
V= Voltage in volts  
I =Current in amps

Figure 7. Total deformation (a) and electrical analysis (b) for carbon fibre sensor subjected to compression loading.
From the figure 7, it can be observed that maximum deflection found to be 5.5 mm corresponding to 95.1 Failure load which is obtained from experimental result. The resistance for failure load is 4.1 kiloohms.

Figure 8. Electrical Analysis of beam (a) and column (b) embedded carbon fibre sensor subjected to flexural and compression loading

From the figure 8, its observed that variation of Electrical resistance of beam for a failure Load of 224.08 kN is found to be 8.33 kilo ohm and for column it is found to be 10.23 kilo ohm for a failure load of 456 kN. The error between is experimental and analytical modelling found to be 15%, hence from these results of the present experimental research it can be concluded, cement carbon composites have great potential and they could be use in concrete field for structural health monitoring applications.

5. Conclusion

The main objective of this work is to develop and embedding sensors into the structural components is successfully achieved. From the experiment and analytical results, it is concluded that structural elements can be made into self-sensing by inclusion of carbon fibre cement composite embedded sensors into it. Since these carbon fibre exhibits piezoresistive properties, these can be used conductive elements into composite. When these composites subjected to stress, strain, deformation, they form conductivity network within composites. Therefore, its possible to measure the change in electrical resistance. The conductive network depends on the types of conductive materials, their amount as well as their distribution. Therefore, these composites can be used as self-sensing smart material to perform health monitoring functions along with strengthening purpose.

References

[1] A. Alessandro, F. Ubertini, A. Materazzi, “Self-sensing concrete nano composites for smart structures”, International journal of civil and Environmental Engineering”, Cement and Concrete Composites, 2016.

[2] S. Laflamme, M. Rallini, A. D’Alessandro, F. Ubertini, “A comparative study between carbon nanotubes and carbon nanofibers as nanoinclusions in self-sensing concrete”, IEEE International Conference on Nanotechnology, 2015.

[3] Faezeh Azhari, Nemkumar Banthia, “Cement based sensors with carbon fibers and carbon nanotubes for piezoresistive sensing”, Cement and concrete composite, 2012.

[4] Shama Parveen, Sohel Rana, and Raul Fangeiro, “A review on nanomaterial dispersion, microstructure and mechanical properties of carbon nanotube and nanofiber reinforced cementitious composites”, Hindawi publishing of nanomaterials volume, 2013.

[5] A. Alessandro, F. Ubertini, A. Materazzi, “Strain measurement in a reinforced concrete beam using embedded smart concrete sensors”, Research gate, 2018.
[6] F. Naeema, H.K. Leeb, H.K. Kimc, I.W. Namd, “Flexural stress and crack sensing capabilities of MWNT/cement composites”, Composite structure, 2017.

[7] A. Alessandro, F. Ubertini, A. Materazzi, “Investigations on scalable fabrication procedures for self-sensing carbon nanotube cement-matrix composites for SHM applications”, Cement and Concrete Composites, 2016.

[8] D. Yeol Yoo, I. You, S. Lee, “Electrical properties of cement-based composites with carbon nanotubes, graphene, and graphite nanofiber”, sensors, 2017.

[9] Fang-Yao Yeh, Kuo-Chun Chang, Wen-Cheng Liao, “Experimental Investigation of self sensing carbon fiber reinforced cementitious composite for strain measurement of an RC portal frame”, International Journal of Distributed Sensor Networks, 2015

[10] Chen, B., Liu, J., Wu, K, “Electrical responses of carbon fiber reinforced cementitious composites to monotonic and cyclic loading Cement and Concrete”, Cement and concrete Research, Volume 35, 2005

[11] Maria S. K. Gdoutos , C. A. Aza, “Self sensing carbon nanotube (CNT) and nanofiber (CNF) cementitious composites for real time damage assessment in smart structures”, Cement and Concrete Composites, 2014.

[12] A. Materazzi, F. Ubertini, A. Alessandro, “Carbon nanotube cement-based transducers for dynamic sensing of strain”, Cement and Concrete Composites, 2013.

[13] E. G. Maciasa, A. D Alessandro, R. C. Trigueiro, D. P. Mirad, F. Ubertini, “Micromechanics modeling of the electrical conductivity of carbon nanotube cement-matrix composites”, Composite part B, 2016.

[14] F. Ubertini, A. D Alessandro, R. C. Trigueiro, E. G. Maciasa “Static and Dynamic Strain Monitoring of reinforced Concrete Components through Embedded Carbon Nanotube Cement-Based Sensors”, Hindawi Shock and Vibration, Volume 2017.

[15] Sohel Rana, Subramani P, Raul Fangeiroiland Antonio Gomes Correia, “A review on smart self-sensing composite materials for civil engineering applications”, AIMS Materials Science, 2016.

[16] M. Sun W. J. Staszewski and R. N. Swamy, “Smart Sensing Technologies for Structural Health Monitoring of Civil Engineering Structures”, Hindawi Publishing Corporation Advances in Civil Engineering Volume 2010.

[17] Carmen Camacho-Ballesta, Pedro Gareces, Emilio Zornoza, “Performance of cement-based sensors with CNT for strain sensing” Advances in Cement Research Volume 28 Issue 4, 2016.

[18] Yining Ding, Zhipei Chen, Zhibo Han, Yulin Zhang, F. Pacheco-Torgal, “Nano-carbon black and carbon fiber as conductive materials for the diagnosing of the damage of concrete beam”, Construction and Building Materials, 2013.

[19] Saptarshi Sasmal1, N. Ravivarman, and B.S. Sindu, “Electrical conductivity and piezo-resistive static and dynamic characteristics of CNT and CNF incorporated cementitious nanocomposites”. Composites Part A, 2017.

[20] A. Sedaghat1, Manoj K. Ram, A. Zayed, Rajeev Kamal, Natallia Shanahan, “Investigation of Physical Properties of Graphene-Cement Composite for Structural Applications”, Open Journal of Composite Materials, 2014.

[21] Rashid K. Abu Al-Ruh, M.ASCE, Bryan M. Tyson, S.M.ASCE, Ardavan Yazdanbakhsh, S.M.ASCE, and Zachary Grasley, M.ASCE “Mechanical Properties of NanoComposite Cement Incorportating Surface-Treated and Untreated Carbon Nanotubes and Carbon Nanofibers”, American Society of Civil Engineers, 2012.

[22] Emmanuel E. Gdoutos, Maria S. Konsta-Gdoutos, Panagiotis A. Danoglidis, Surendra P. Shah. “Advanced cement based nanocomposite reinforced with MWCNTs and CNFs” Front. Struct. Civ. Eng. DOI 10.1007/s11709-016-0342-1.

[23] Roopa A.k, A.M. Hunashyal, Pallavi Venkaraddiyavar and Sharanabasava V. Ganachari “Smart hybrid Nano-composite concrete embedded sensors for structural health monitoring application” , Materials Today Proceeding, Volume 27, Part 1, 2020

[24] Ubertini, F., Lafllame, S., & D’Alessandro, A, “Smart cement paste with carbon nanotubes” Innovative Dvelopments of Advanced Multifunctional Nanocomposites in Civil and Structural Engineering, 2016.
[25] Rainieri, C., Song, Y., Fabbrocino, G., Markand, J.S., Shanov, V., “CNT-cement based composites: Fabrication, self-sensing properties and prospective applications to Structural Health Monitoring”, Fourth International Conference on Smart Materials and Nanotechnology in Engineering, 2013.

[26] Hunashyal AM, Tippa Sagar V, Quadri SS, “Experimental investigation on effect of carbon nanotubes and carbon fibres on the behavior of plain cement mortar composite round bars under direct tension”, ISRN Nanotechnology, 2011.

[27] Hunashyal AM, Sundeep GV, Quadri SS, “Experimental investigation on effect of carbon nanotubes with cement-based matrix on plain cement composite beams”. Nano engineering and Nano systems 2011.

[28] J. Sebastian, N. Schehl, M. Bouchard, M. Boehle, L. Li, A. Lagounov, K. Lafdi, “Health monitoring of structural composites with embedded carbon nanotube coated glass fiber sensors”, Carbon Volume 66, January 2014.

[29] Zhang, W. Suhr, J. Koratkar, N. “Carbon Nanotube/Polycarbonate Composites as Multifunctional Strain Sensors”, Journal of Nanoscience and Nanotechnology, Volume 6, Number 4, April 2006.

[30] Shaowei Lu, Lu Zhang, Caijiao Tian, Xiaqiang Wang, Duo Chen, “Health monitoring for composite materials with high linear and sensitivity GnP/epoxy flexible strain sensors”, Sensors and Actuators A: Physical Volume 267, 1 November 2017.

[31] Filippo Ubertini, Simon Laflamme, Halil Ceylan, Annibale Luigi Materazzi, Gianluca Cerni, Hussam Saleem, Antonella D’Alessandro and Alessandro Corradini, “Novel nanocomposite technologies for dynamic monitoring of structures: a comparison between cement-based embeddable and soft elastomeric surface sensors”, Smart Materials and Structures, Volume 23, Number 4, 2014.

[32] Antonella D’Alessandro, Filippo Ubertini, Annibale Luigi Materazzi, “Electromechanical modelling of a new class of nanocomposite cement-based sensors for structural health monitoring”, research article, 2014.