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Research Article

Structural Health Monitoring of Nonwoven Materials via Network of Carbon Nanotubes

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Abstract— Continuous health monitoring of structures is crucial in order to ensure the safety of the people living in and around the structures made up of nonwoven materials. Carbon Nanotubes (CNTs) used as sensor show a promising way of detecting these damages and relaying the signals in order to prevent any major accidents. In this study, MWCNT – multi walled carbon nanotube have been used to decorate glass fiber nonwoven material by using vacuum filtration method. Experiments have been done on CNTs decorated nonwoven of different dimensions, i.e. virgin, horizontal pre-damaged, diagonal and vertical pre-damaged specimens. The electrical resistance of CNT decorated nonwoven material has been measured by increasing the tensile force simultaneously followed by evaluating the damage fruition and electric failure mechanisms in the glass fiber nonwoven material. The experimental results show that MWCNT loading as small as~0.75% was enough to detect the damage in the nonwoven material. This process can be scaled up and used extensively for structural health monitoring of nonwoven materials.

Keywords— Non-woven, Carbon Nano tubes, Multi-walled Carbon Nanotubes, Structural heath monitoring, non-woven materials, Glass fiber Nonwoven.

1. Introduction

Nonwoven materials are complex three-dimensional (3D) structures made up of long and short fibers. Unlike woven fabrics (interlacement of warp and weft yarns) and knitted fabric (serious of loop formation), non-woven fabrics are formed by bonding methods like thermal, mechanical or chemical. Typically these materials are categorized as wet laid, dry laid and polymer laid. Wet laid is used for papermaking, dry laid used in textiles origin and polymer laid plastic productions [1].

Nonwoven fabrics are frequently bounded with the use of a backing mediator. They can be single-use but fundamentally very durable. They are manufactured for a variety of purposes. Mostly their functions including flame retardancy, porousness, thermal insulation, absorbency, and filtration are among many other functions [2].

Glass fiber nonwovens are nonwoven fabrics made from glass fiber. Geotextiles, civil constructions, industries, hospitals, and aerospace are the widest application areas of glass fiber nonwoven fabrics. Any structural systems of constructions including aerospace, civil, mechanical, and pavement structures or others are subject to various factors, Hence in their nature of structural systems, they undergo elderly and decline while in service due to the lack of quality of construction, bad situations happened from accidents or environmental deterioration and an incorrect construction process. Because of this, SHM – Structural Health Monitoring is very important in order to maintain their reliability and consistency during their service life. Hence, the main one is the structural health monitoring of nonwoven material via a network of carbon nanotubes. To detect these changes in the structure and material and to react in a proper way before thoughtful damage caused, the implementation of damage identification technique is very important [2-3].

Some test results expressed that an individual SWNT – Single wall Nanotube has greater room temperature and thermal conductivity when compared to another materials having good thermal conductivity [4]. Carbon nanotubes are known by forming a network of conductive tubesso that their mechanical properties are consequential from strength, tenacity and stiffness. Hence they have greater conductivity as well as aspect ratios [5-7].

Naturally, carbon nanotubes are enriched with electronic and mechanical properties which make them widely used in different applications. These properties i.e. electrical resistance and mechanical deformation indicating that carbon nanotubes both single and multi-walled can be used as strain-stress sensors [8].

This study focused on systematically design and develops the non-woven coated network of carbon nanotubes for real – time monitoring during end use application.

2. Related Work

While conducting this research work, the following research papers have been referred.
Hu, Ning, Hisao Fukunaga, Satoshi Atobe, Yaolu Liu, and Jinhua Li. Studies the significant developments in the field of highly sensitive strain sensors made from CNT/polymer nanocomposites. Their study was focused on electrical conductivity and piezoresistivity of CNT/polymer nanocomposites [8].

Könemann, Fabian, Morten Vollmann, Tino Wagner, Norizzawati Mohd Ghazali, Tomohiro Yamaguchi, Andreas Stemmer, Koji Ishibashi, and Bernd Gotsmann have extracted temperature-dependent thermal conductivity values from scanning thermal microscopy measurements of a self-heated multiwalled carbon nanotube supported on a silicon substrate. A deliberately introduced segment of amorphous carbon served as an integrated nanoheater. They found that thermal conductivity values that continuously increase in a temperature range of above room temperature [10].

Nag, Anindya, Md Alahi, E Eshrat, Subhas Chandra Mukhopadhyay, and Zhi Liu. Also stated in their study that the MWCNT-based sensors have been able to deduce a broad spectrum of macro- and micro-scaled tensions through structural changes [11].

3. Theory/Calculation

The critical volume fraction of CNT which is used to know the least amount of CNT applied on the nonwoven material surface to determine the electrical conductivity will be computed using Komori and Makishima model [13].

$$\mu^{KM}{}_{C} = \frac{\pi}{5.77\ SI} \qquad (1)$$

The ratio of length (l) to diameter (d) which is aspect ratio of the rod is given as the following.

$$S = \frac{l}{d} = \frac{23.94\mu m}{14.1nm} = 1698 \qquad (2)$$

Whereas, 'I' defines alignments of Carbon nanotube. Its value is equal with $\frac{2}{\pi}$ [23]. Therefore, the minimum weight of CNT

required measuring the characteristics of surface parameters of CNT decorated nonwoven material, its critical volume fraction (μc) is calculated as equation (1) above.

$$\mu_c = \frac{\pi}{5.77\frac{2 * 1697.8}{\pi}} = 0.05\ \%$$

4. Experimental Method/Procedure/Design

Glass fiber nonwoven fabric and Carbon Nanotube, Distilled water, ultrasonication time, power supply and multimeter have been used. Table 1 and 2 gives the details of glass fiber nonwoven and carbon nanotube properties and ratios used for the study.

Table 1. General Properties of Nonwoven materials and CNT

Type of Material	Property	units	values
Glass fiber non-woven	Mass per unit area	g/m^2	231.2 +/- 0.5
	Thickness	mm	1.44 +/- 0.05
Carbon nanotubes	Initial volume fraction of CNTs	-	0.05

Table 2. Required ratios of CNTs, distilled water and ultrasonication time

Weight of CNTs(mg)	Distilled water volume(ml)	Ultrasonication time (hr.)
5	100	3
10	100	3

Methods of preparing CNT decorated nonwoven material through vacuum filtration
CNT had been dispersed in distilled water and stirred by ultrasonication in a bath, sonicated for 3 hours. By depositing CNTs Solution on to the preselected glass fiber nonwoven, an electrically-isotropic nanotube network will formed on the surface of glass fiber nonwoven. Vacuum filtration will held by Brosil glass flask followed by drying the CNT decorated composite at 70°C for 7 hours in order to hold the CNT network inplace. Then Small part of specimen cut from coated glass fiber nonwoven, and strain sensor test held on by loading the specimen on test frame and slowly applying tensile force following by measuring its electrical resistance change. The thickness of Glass fiber nonwoven before and after CNT applied to glass fiber nonwoven also measured for both 0.75 and1.5 wt. % CNT.

Electrical resistance will be measured by multimeter (two probes) device at different strain value of percolated nonwoven via different percentage (0.75 and 1.5 wt. %) loaded network of CNT. These have been done by clamping one side of the sample at the fixed jaw and another side on the mobile jaw on frame test followed by connecting the two probes on both sides to the CNT coated nonwoven, then by giving tensile load, the electrical resistance measured till the CNT network broken at high strain value. Hence it senses the damage by giving zero resistance reading. During carrying out the required experiment the spacemen prepared in appropriate size (30 mm height x 7 mm width).

Methods of Electrical Conductivity Test
To perform the electrical conductivity test, two different methods have been used;

The first is direct reading electrical resistance from connected digital two probe multimeter while tensile load applied slowly to sense the damage of the specimen. All such sensor readings will recorded while the load is given manually by rotating the screw of the frame test on which copper wire and carbon nanotube coated nonwoven connected together. The extended length because of applied load will be measured by scale to calculate strain. The initial distance between frames bar (gauge length) is set to 15mm.

The second method is converting voltage and current flow through specimen due to CNT to electrical resistance. In this method, in order to calculate the electrical resistance of CNT coated glass fiber nonwoven, voltage (v) and electric current (A) will be measured. Then the resistance will be calculated by Ohm's law formula.

$$R(\Omega) = \frac{Voltage\ (V)}{Current\ (A)} \quad (3)$$

To do this experiment, power supply, multimeter, and frame test on which the specimen loaded was used. By clamping the CNT decorated nonwoven with two copper wires on both ends of sample and giving voltage (5v), the current flow through the sample was recorded at different strain range till the CNT on nonwoven surface broken (maximum strain). Then resistance is calculated by the formula stated in equation (3).

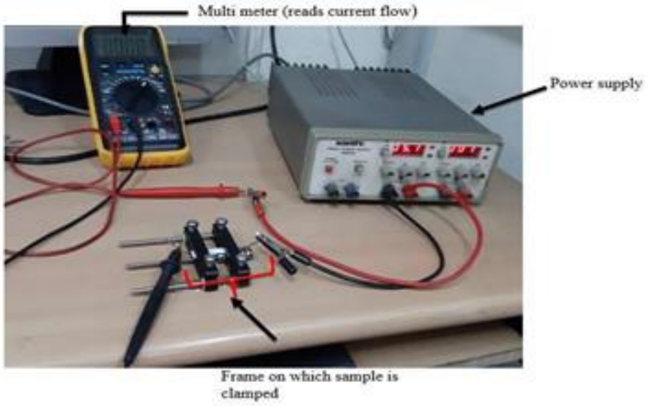


Figure 1 indirect reading measuring of electrical resistance for CNT decorated nonwoven

A digital multimeter having double point probe will be used to measure current flow through the coated nonwoven. The CNT decorated nonwoven material is subjected to tension while the incremental tensile loading is applied. The voltage from power supplier is kept constant and the current is flow across the two probes and passed through the specimen. To check the flow of current, LED bulb that emit light has been used.

CNT decorated nonwoven dimension changes due to applied tensile load results the change in current flow through it; hence there is a change in resistivity of the CNT decorated glass fiber nonwoven. Another methods used to check whether CNT has been used as strain sensor or not is by using LED bulb that emit light during normal (unbroken) of CNT film on nonwoven structure because of current flow through it and give no light when the CNT decorated on nonwoven damaged hence can sense the health of the structure without using any calculation.

5. Results and Discussion

Fourier-transform infrared spectroscopy of carbon nanotube (FTIR)

FTIR is the optical characterization which is commonly used to examine the functionality of carbon nanotubes. Also it could be considered under the heading of defects. Investigate functionalization of carbon nanotubes which one could also consider under the heading of defects. The extent of functionalization is carried out in the range of 400-4000cm^{-1}.

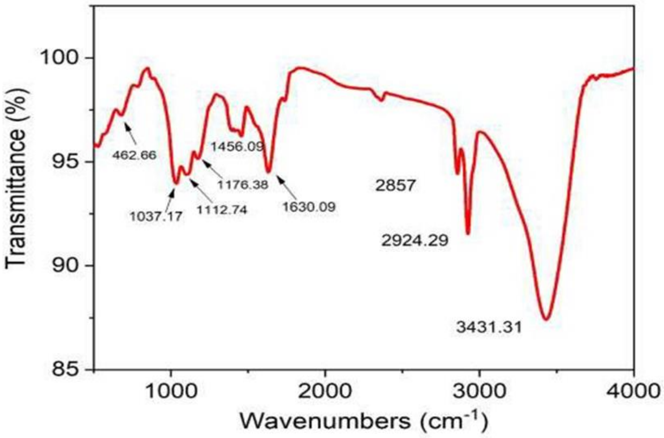


Figure 2. Fourier-transform infrared spectroscopy of CNT decorated glass fiber nonwoven.

In this experiment, FTIR study was conducted in the range of 400-4000cm^{-1}. As it is observed from the figure 3, the result shows dominant peaks at 1037.17, 1112.74, 1176.38, 1456.09, 1633.4 cm^{-1} which matches to Si-O, C-N, NH_3, C-N, C-O respectively.

Electrical Conductivity of CNT decorated glass fiber Nonwoven

The CNT decorated nonwoven material is prepared for tensile testing and electrically conductive sensors with rectangular dimension of length 30 mm, and width 7 mm) cut from the CNT decorated glass fiber nonwoven as indicated under Figure 4.

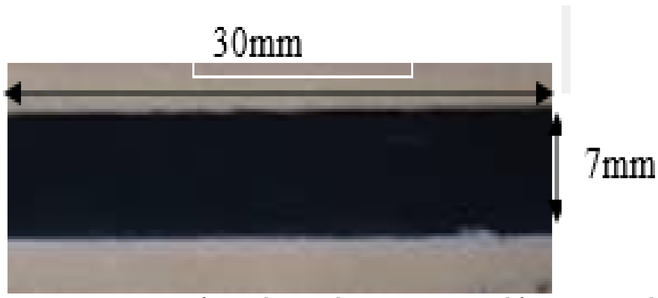


Figure 3. Dimension of CNT decorated nonwoven material for testing tensile and electrical Conductivity sensor

For different percentage load of CNT decorated nonwoven materials, strain and conductivity have measured by giving pre-damage to the sample at different angles along the cross direction of nonwoven material and without pre-damage to monitor the early damage of CNT decorated nonwoven material for electrical conductivity and strain sensor performance. Pre-damage was given at 45^{O}, 90^{O} and 180^{O} all with the same damage length (5mm) on the side of uncoated nonwoven by CNT film as shown in Figure 4.

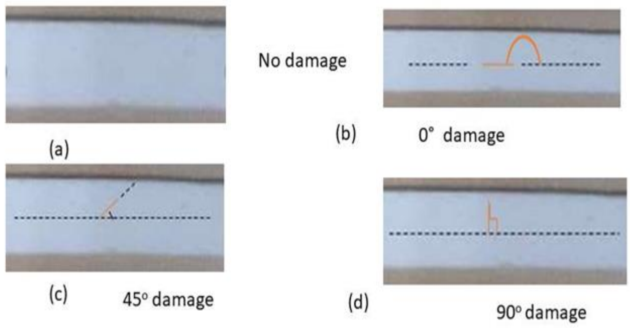


Figure 2. Pre-damages of Samples at different angles

To measure the electrical resistance we used three methods, direct reading from multimeter, by calculating from current and voltage from power supply and by using LED for checking current flow through specimen till the sample will damage.

Average Weight (0.75 wt. % CNT) loaded on Nonwoven

Table 3**.** Electrical Conductivity test result of CNT decorated Nonwoven material at 0.75 wt.

Test No	Gauge Length (mm)	Strain (%)	Change in Resistance (%)
	15.00	0.00	0.00
	15.08	0.53	24.39
I	15.13	0.87	29.41
	15.20	1.33	59.09
	15.28	1.87	120.00
	15.35	2.33	324.24
	15.42	2.80	0.00
	15.00	0.00	0.00
	15.15	1.00	17.14
II	15.21	1.40	46.34
	15.26	1.73	25.00
	15.33	2.20	46.67
	15.39	2.60	100.91
	15.44	2.93	304.07
	15.52	3.47	0.00
	15.00	0.00	0.00
	15.12	0.80	5.13
III	15.23	1.53	26.83
	15.31	2.07	38.46
	15.35	2.33	66.67
	15.38	2.53	141.67
	15.41	2.73	279.31
	15.48	3.20	0.00

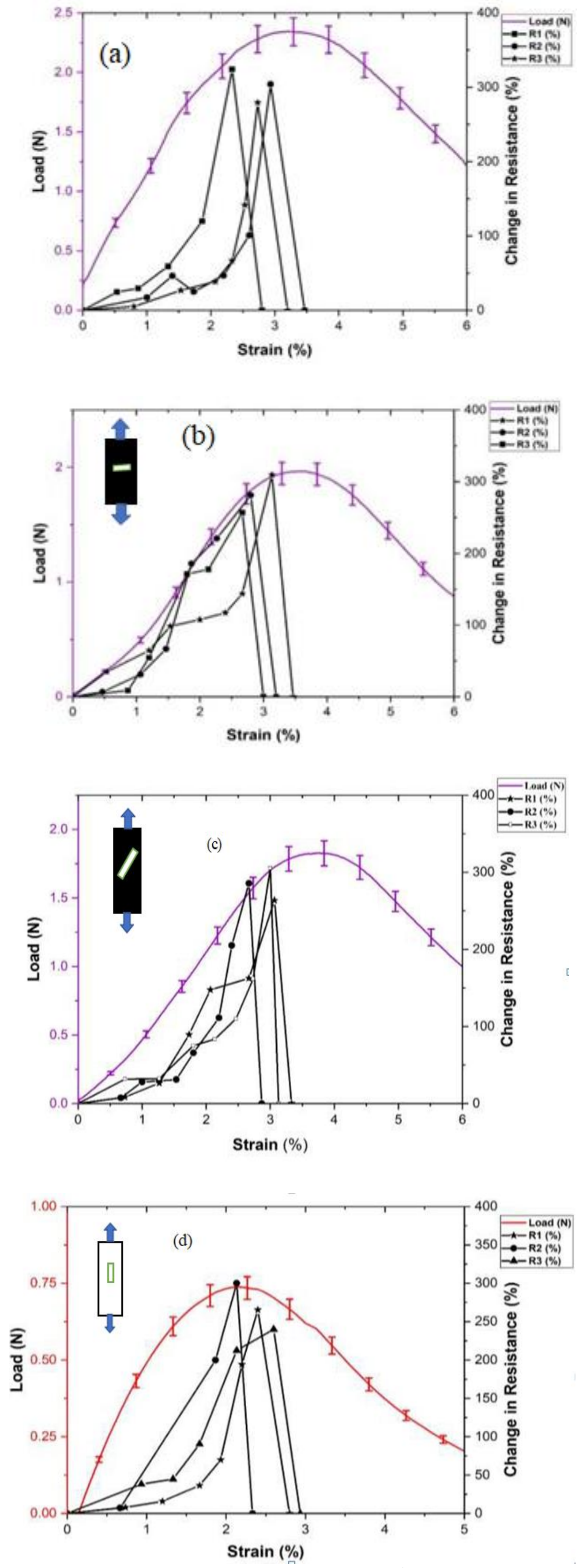


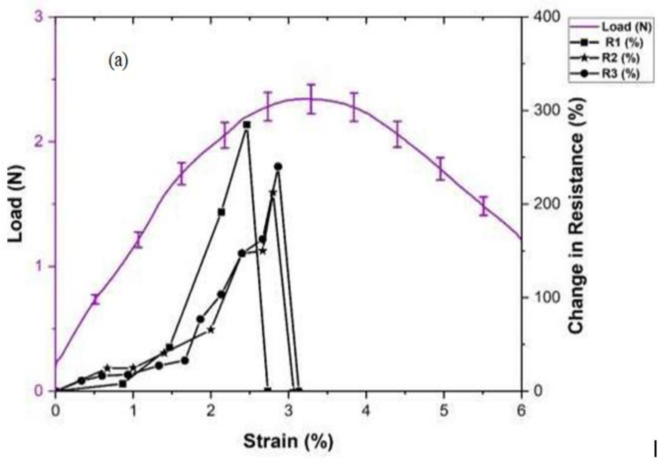
Figure 5. Typical Load-Strain-Resistance response of CNT coated nonwoven (0.75wt. %loaded)(a) at virgin,(b)horizontal pre-damaged, (c)diagonal and(d) vertical pre-damaged samples.

Under these load strain versus electrical resistance graph, as shown Figure 6 tabulated in table 3 the CNT decorated nonwoven used as a sensor for damage at the maximum average tensile force of (2.4, 2, 1.8, 1.3) N and average electrical resistance of (302.54, 282.5, 284.8, 288.44) % respectively. The normal sample (undamaged) takes more tensile force to break having average strain level of 3-4 % and it shows more change in electrical resistance. But for samples given vertical pre-damaged the strain level is 2-3 % and damaged earlier so it shows that less change in electrical resistance. Hence CNT film coated on the surface of nonwoven can sense the damage of structure earlier. However, the strain of material on which it applied and its characteristics has an effect on the ability of CNT to sense damage on time.

Average Weight (1.5 wt. % CNT) loaded on Nonwoven

Table 4. Electrical Conductivity Test Results of CNT decorated Nonwoven material at 1.5 wt.

Test No	Gauge Length(mm)	Strain (%)	Change in Resistance (%)
	15.00	0.00	0.00
	15.13	0.87	8.00
I	15.22	1.47	47.06
	15.32	2.13	191.43
	15.37	2.47	284.62
	15.41	2.73	0.00
	15.00	0.00	0.00
	15.10	0.67	24.44
	15.15	1.00	24.83
	15.21	1.40	40.82
II	15.30	2.00	65.70
	15.36	2.40	147.20
	15.40	2.67	150.00
	15.42	2.80	212.50
	15.46	3.07	0.00
	15.00	0.00	0.00
	15.05	0.33	11.11
	15.09	0.60	16.50
III	15.14	0.93	17.61
	15.20	1.33	27.38



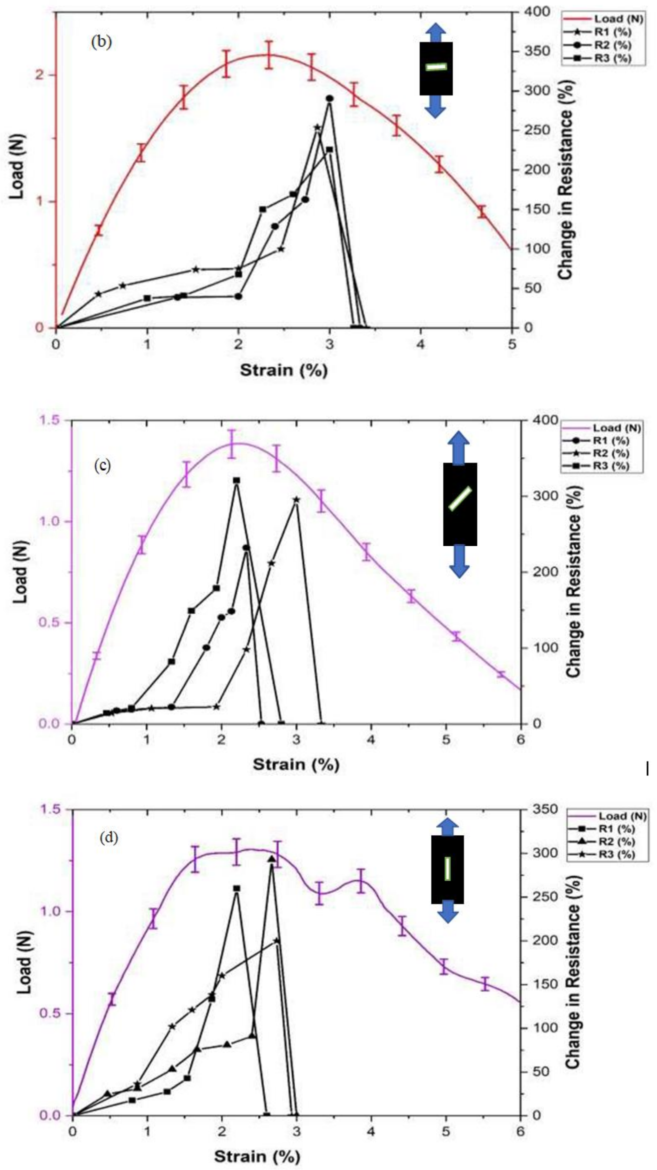


Figure 6. Typical Load-Strain-Resistance response of CNT coated nonwoven (1.5wt. %loaded) (a) at virgin, (b) horizontal pre-damaged, (c) diagonal and (d)vertical pre-damaged samples.

Under these load strain versus electrical resistance of graph, the CNT decorated nonwoven used as a sensor for damage at the maximum average tensile force of (2.4, 2.15, 1.31, 1.25) N and average electrical resistance of (245.71, 256.8, 282.96, 250.9) % respectively.

The resistance-strain responses of CNT decorated glass fiber nonwoven for strain sensors by different amount of CNT loading are shown in Figures 7 tabulated table 4 above. This result implies that electrical conductivity of CNT decorated nonwoven be contingent on various factors such as polymer matrix, quality of dispersion and aspect ratio.

Tensile load curve, the load (N) applied by Tensile testing machine is not related with the CNT film coated on the surface of glass fiber nonwoven for strain sensor, yet it was used for determining the strain of the glass fiber nonwoven material. But the strain obtained by frame test is correlated with the strain sensor of CNT decorated nonwoven, because during performing strain sensor experiment on frame test, the two probe multimeter was connected to the CNT film surface so that as the CNT particles on nonwoven surface starts to broken due to slightly increasing tensile load, the electrical resistance increasing slowly and suddenly zero when the CNT has completely broken. The electrical resistance average was recorded followed by the strain at which the CNT film has broken. Hence our objective is to notice how CNT is used for strain sensor while applied on glass fiber nonwoven.

6. Conclusion and Future Scope

In this study, glass fiber nonwoven materials were decorated with commercially available Multi-walled Carbon Nanotubes (MWCNTs) using a simple, facile and scalable vacuum filtration process. The experiment has been done by giving different angled artificial damages to the sample. It can be utilized to detect any deformation in these MWCNT decorated glass fiber nonwoven structures allowing to take any preventive steps before its failure. Regarding to effect of weight percentage loading of MWCNTs on nonwoven material, the study shows MWCNT decorated glass fiber nonwoven material can be used in structural applications so that any possible failures in the structure can be easily detected. Furthermore best strain sensing ability of the MWCNT decorated glass fiber nonwoven material was obtained at an average MWCNT concentration of 0.75 %. This means that a very small amount of MWCNTs is enough for sensing any deformations in the structural composites.

Glass fiber nonwovens exhibit wide range of applications like in building, aerospace, industry, etc. The Structural health monitoring can be controlled by introducing CNTs to nonwoven materials. CNTs have huge scope in detecting the damage or rupture of structures. So that for the future scope, Present work will be extend to: -

- Studies involving nonwovens other than glass fiber nonwovens.
- Pre-damages other than horizontal, diagonal and vertical slits will be studied.
- designing the wireless CNT strain sensor by network application also a part of this study.

Data Availability (Size 10 Bold)

The data supporting findings of this study are all presented in the article.

Conflict of Interest

The author declare no conflicts of interest

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