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The use of nanosensors for monitoring civil structures

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Abstract

Nano-sensors were tested to demonstrate whether nanotechnology could be obtained efficiently in the civil engineering field. The objective of the experiment was to reach a specific amount of resistance and electric conductivity produced by the sensors, which were later compared to other researches. The sensor was fabricated using carbon nanotubes (CNT) more specifically multi-walled carbon nanotubes (MWNT's) as a conductive material and Polydimethylsiloxane (PDMS) as a polymer. Three samples were made with different CNT percentages. The material was then coated on a compact tension specimen and tested in tension. The results obtained were positive. The coating materials contained a good amount of resistance. Fabricated tube shaped coating materials were additionally tested on their ductility. The calculated electric conductivity correlated well when compared to other researches. Therefore, it was concluded that nano-sensors could be fabricated with the results obtained. However, to improve the main experiment conducted, a slightly more brittle compact tension specimen is recommended to obtain better and more accurate results.

Introduction

The emphasis of this paper was to implement nanotechnology, a new option in renewable energy, to civil engineering structures. The challenge is to create a product that would generate enough resistance and electrical conductivity to be able to be used in such structures. The increase in the world's population means the demand of energy will only increase (Boluk and Mert, 2014). Since fossil fuels are the main source of energy, which produce greenhouse gases and directly affect climate change, new types of cleaner energy will be needed such a renewable energy (Boluk and Mert, 2014). There has been different types and project sizes of renewable energy. Most renewable energy projects are focused solely on the larger scale projects such as solar, wind and heat energy. However, they tend to need a large amount of space in order to work efficiently (Yue et al., 2015). Smaller scaled projects used in the micro scale are gaining more interest due to their positive abilities in electric conductivity and mechanical strength (Das et al., 2017). In this paper, one specific part of this innovative technology will be tested and analysed to further implement it in civil structures to aid the larger projects in reducing or slowing climate change. Creating a nano-sensor that can produce a fair amount of resistance and electrical conductivity to be used to monitor deflection, bending, and more seriously, cracks will be the projects aim.

The experiment will contain different parts from fabrication to testing. The fabrication process will contain the use of multi-walled carbon nanotubes (MWNT's), one type carbon nanotubes (CNT), which is a conductive material. Added to it, is Polydimethylsiloxane (PDMS), which will act as the polymer. Additionally, Acetone will be added to the mix to ease the dispersion process. Two different weight percentages of CNT will be used with respect to PDMS, which are 3% and 5% CNT. The reason was to compare the samples in resistance and electric conductivity. When the materials are fully dispersed, Silicone elastomer, a solidifier will then be applied and mixed thoroughly. The materials will then be coated on three aluminium compact tension specimen. 3% and 5% CNT samples will contain the same thickness. The third sample will be a 5% CNT, however, will differ in the thickness of the coating material to test its ductility. Six additional tube shaped samples will be made to test the materials conductivity. When the sensors fully solidify, silver paint will then be applied on the all samples to increase their conductivity. The samples will then be ready for testing.

Resistance will be recorded in Ohms using a multimeter. An initial resistance will be recorded before tension is applied on the sample. The test will contain six pauses. At each pause, resistance will be measured. When all measurements are collected, electric conductivity will be calculated to test whether the sensor reached its aim.

The second test conducted was experimenting the tube shaped samples resistance and tensile strength.

If successful, the sensor will be able to be implemented in the civil engineering field. The sensor can be used in different structures such as beams, roads, and bridges. The aim is to use nano-sensors in structures such as bridges to monitor bending, deflection or cracks, which would give early indications of a fault occurring without the need to use of fossil fuels or batteries to power the sensors.

Procedure

Equipment used

Devices, which were used in the fabrication process:

- Sartorius scale used to measure the composites weight.
- An engineering bench vise that holds the aluminium plate for the pre-crack process.
- Ultrasonicator, which was used to disperse CNT and PDMS in the acetone.
- Water jet cutting machine to cut the aluminium plate to specifications.

Facilities and devices used in the experiment section:

- Instron 5582 shown in Figure 1 was used to test the aluminium compact tension plate in tension.
- Multimeter was used to measure the resistance of the composite which increased with the application of tension
- Instron 3345 shown in Figure 2 was used to test the tube shaped nano-sensors in tension.

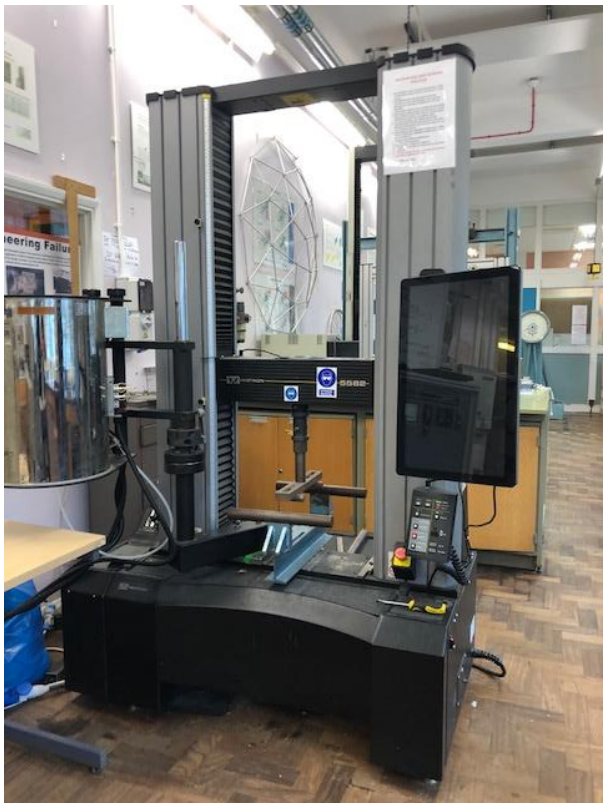

Figure 1: Instron 5582 used for tensile testing CT specimen.

Figure 2: Instron 3345 used for tensile testing tube shaped sensors.

Fabrication

Carbon nanotubes (CNT) were placed in three small plastic containers with a screw head. Each container was labelled with different percentages of CNT; 2%, 3%, and 5% as shown in Figure 3. To calculate the weight of CNT needed in each container, the weight of Polydimethylsiloxane (PDMS) was required to be determined. It was decided that 20 grams of PDMS will be used. Therefore, the weight of 2% of CNT equalled $20\ grams\ (PDMS) \times \frac{2}{100} = 0.4$ g of CNT in the first container. Using the same formula, 3% CNT = 0.6 g, and 5% CNT = 1 g. The CNT was weighed approximately using an accurate scale shown in Figure 4, with a margin of error of $\pm$0.05g. 40 grams of Acetone was weighed in on a similar scale, then, added in the mixture to act as a solvent through the next stage.

Figure 3: Labelled containers containing the composite.

Figure 4: Sartorius scale for sample weight measuring.

Due to the material's inability to disperse by regular mixing, a special machine was needed. The ultrasonicator was then used to disperse the CNT and PDMS. Aditionally, Acetone was used to aid in the dispersion process. As shown in Figure 5, the ultrasonicator is a device, which uses ultrasonic sound waves to disperse nanoparticles in a solvent. The dispersion process was divided in to two rounds for all three containers. Each container took approximately 2 minutes a round while moving in circular motion to fully disperse the CNT in the solvent. Twenty extra grams of Acetone was then added to the material to get an improved mixture. The 20 grams of PDMS was then added to all three containers. The ultrasonicator was then used to disperse the composites in all containers once more. However, the ultrasonication process took about 5 minutes for each container to dissolve well in the second attempt. All three containers were then placed in an oven with a temperature of 60 degrees Celsius for 3 days to evaporate the acetone from the mixture. The mixtures were then ready to use after being checked if the Acetone fully evaporated out of the containers.

Figure 5: Ultrasonicator dispersing CNT/PDMS.

The aluminium plate was cut using a water jet-cutting machine to the specifications needed. The dimensions of the plate were then decided and drawn on AutoCAD, which is shown in Figure 6. The dimensions used were according to a previous sample prepared at the University of Plymouth. The cutting process was then carried out by a technician in the laboratory. The aluminium plate was then pre-cracked in its centre by using an engineering bench vise to hold the sample in place and pre-cracking it to with a saw to a distance of 5mm.

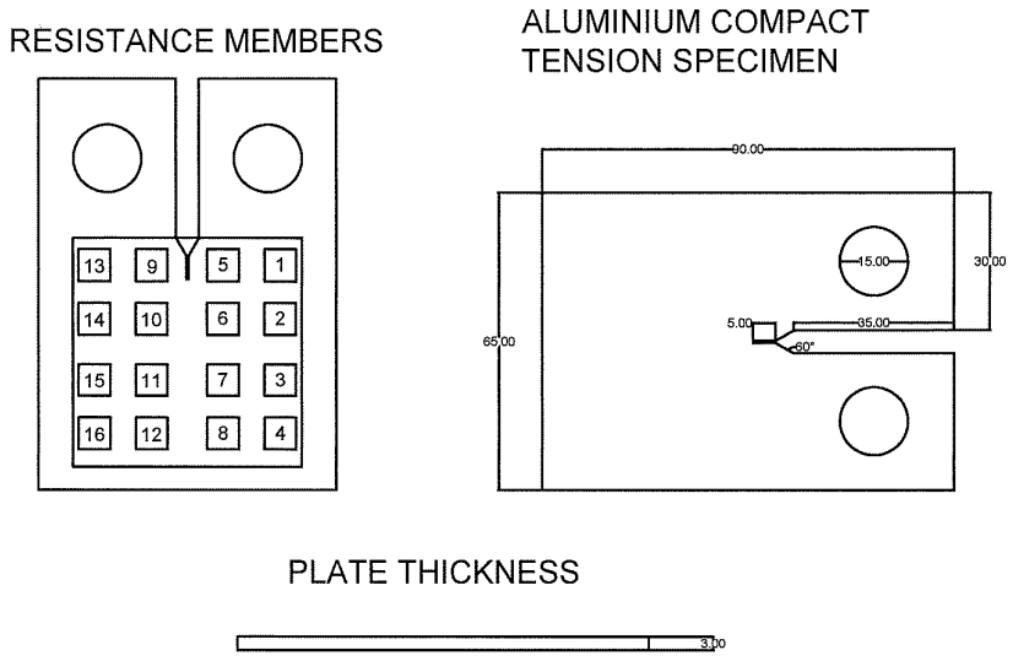

Figure 6: AutoCAD drawing of Compact tension specimen.

Once the samples were made, a plastic sheet (Acetate), with a thickness of 1mm, was cut to the dimensions of the aluminium compact tension specimen. A 5x5 cm square shape was then cut from the centre of the plastic using a utility knife to allow space for the coating material to be applied between it. The cut plastic was later placed and taped on the aluminium plate from its edges to disallow any movement while applying the coating the material. A rubber material was then put in the engineered notch to allow the material to solidify above it for better results.

To not waste the coating material which was made, a specific amount of the material, which was decided by its weight was taken and put in a paper cup. This was done to only allow the desired amount to be solidified for the next stage. This step was done to all 3 percentages of CNT with different cups for each material.

The first examination made was on the 3% CNT. It was decided to glue together two of the cut 1mm plastic sheets to have a thicker coating material applied on the aluminium to test ductility. The glued plastic sheets were then taped on the aluminium plate to allow the coating process to begin. Silicone elastomer curing agent, a solidifier, was then added to the energy harvesting material that was in the paper cup. It was decided that the weight of the added solidifier would be a ratio of 0.1 the weight of the coating material due to it being a standard ratio added to

solidify the material. When added, the mixture was then mixed thoroughly to allow the energy harvesting material to fully solidify.

The mixture was then coated in the 5x5 cm cut square shape, which was placed in the centre of the cut acetate sheets taped on the aluminium. When fully covered, the energy harvesting material was flattened using the sides of a straight plastic sheet. The coating material started to solidify slowly while it was being applied and flattened. Therefore, the acetate was carefully removed to avoid disrupting the material and it getting soft, which might cause melting when put in the oven in the next stage.

An additional coating material applied into a silicon tray shaped into tubes or sticks created 3 samples. The composite was placed in an oven for 4 days at a temperature of 60°. The material was later tested on its strength in tension.

Similarly, 5% CNT required an identical procedure in fabrication to the 3% CNT. However, two samples of the coating material were made with different thicknesses to test the differences between their resistance and durability. The first sample included one sheet of acetate to obtain a coating material with a thickness of 1mm. Similar to the 3% CNT, the second sample involved two 1mm acetate sheets glued together to gain a coating material thickness of 2mm.

An additional 5% CNT mixture was created containing 12g of PDMS and 0.6g of CNT. The same procedure mentioned above was used in fabrication to create an additional 3 tube shaped samples, with different CNT weight percentages. The results were compared in later stages.

The same procedure was followed for the 2% CNT fabrication. However, only a 1mm coating material thickness was made, due to its inability to be a conductive material when a quick inspection of resistance was conducted.

All samples were then put in an oven with a temperature of 60° to aid in fully solidifying the coating material. The 4 aluminium plates containing the nano-sensor samples were put in the oven for 2 days, while the silicon tray was in for 4 days. It was then determined that the samples were ready for testing once they were fully solidified and no excess adhesive layer was found.

The final step of fabrication was applying dots of pure silver paint on the coating material, which was applied on the compact tension specimen to reduce any excess resistance that can occur when tension will be applied. It was decided that 16 dots/resistance members will be painted and numbered with 4 rows and 4 columns, to make a symmetrical shape as shown in Figure 6. The reason for this decision was to get accurate readings of resistance with the multimeter. Once dried up, the samples were ready to be put into testing.

Pure silver paint was also applied on all six tube-shaped samples. However, only two lines of paint were applied in the centre of the composites to measure resistance, assuming that the samples will fail from their centre when tested in tension. Once the silver paint had dried up, the final step was to apply copper plate tape on the lined silver paint to reduce excess resistance.

Testing

The first experiment that was conducted was testing the aluminium plate in tension using Instron 5582 while also recording the resistance made by the coating material. The first step was to test a sample of a pure aluminium plate, which was not hybridised with the coating material.

The idea of testing the aluminium purely was to get an understanding of the behaviour of the material and how it reacts when a force is applied on it, such as tension. An example would be understanding if a crack would develop when placed in tension. If so, would it grow in the same progression and direction in all cases? Would the aluminium plate buckle while the tensile stress is applied on it even with the addition of a pre-crack?

To examine whether the aluminium plate will obtain what was questioned, a tensile test using the fatigue test machine was used. The specimen was placed between the top and bottom clamps using the control box, which adjusted the distance of the locks to enable the plate to be bolted. Using the control box once more, the distance was increased to disallow any unnecessary movements in the plate from occurring. The device was zeroed and the speed of displacement was decided to be 5mm per minute using the monitor screen on the machine. Once the instrument was set up, the testing begun. It was noticed that a crack started to develop once the displacement exceeded 5mm. With the continuation of force being applied on the plate, the crack kept on increasing in size. The crack's pattern was going downwards in a straight line before curving further down the plate. It was also noted that the aluminium plate started to buckle slowly once the tensile force was applied on it. However, it started to increase with the continuous forces applied on it.

Since aluminium is a predictable material in its reactions to force, and the fact that all plates were made out of the same type of aluminium, it was assumed that the plate would behave similarly in all cases. The crack would develop in a specific way and direction, while the plate would buckle similarly for all tests.

Before using the fatigue test machine to examine the samples in tension, a reading of resistance for all sensors was required using a multimeter. This was done in order to compare the results before and during the application of tension was applied on the material. The multimeter was turned on and set to Ohms (Ω) to record resistance. The red and black cables were then placed on the numbered silver paint dots aligned horizontally as shown in figure 6. Resistance data was collected by moving downwards from the top right of the sample ending in the bottom left of the model. Once the readings for all samples were recorded, the specimens were then able to be tested when tension was applied.

Similar to the tensile test for the pure compact tension plate, the hybrid nano-sensor was placed between the top and bottom clamps of the machine. With the aid of the control box, the clamps were adjusted to a level where the aluminium plate can be bolted through its grips. Small steel plates were placed on each side of the aluminium plate to reduce any type of bending from occurring. The sample was then bolted to the clamps.

The machine was then adjusted using the control box, by increasing the height of the top clamp so the plate was stable without any movements. The device was then zeroed using the monitor screen. While using the monitor, the momentum of

displacement for the device was then decided to be set at 5mm per minute. The test was then named to the percentage of the CNT. The tension process then started after the device was set and the test was named. The device was paused approximately every 5mm of displacement and new measurements for resistance were taken to understand how resistance increases when put under tension. Measuring resistance was similar to the first reading by using the red and black wire aligned horizontally while taking measurements downwards. However, the sample was put between the clamps and under tension, causing the way of taking the reading slightly tougher. The process was repeated 5 times with different measurements taken at each pause. During the procedure, it was noted that the resistance got higher by the increase of tension applied on the energy harvesting material. A crack was also noticed after a displacement of 5mm, which started to develop and was later measured and added in the result section. It was also inspected that the aluminium started to twist and buckle. A total of 6 measurements for resistance were taken for each plate, the results were then saved in the device and added to a USB.

Another important observation was made on the 2% CNT. While testing its resistance before the tensile test was made, it did not conduct any resistance and no results were concluded. Therefore, it was assumed that 2% CNT did not have enough carbon nano-tubes to be an energy harvesting material and no tensile testing was made on it.

The second experiment conducted was testing the ductility of the tube shaped nano sensors shown in Figure 7 while recording the resistance made by the coating material. The aim was to get to understand the strengths of the materials containing different CNT percentages. All samples were numbered to avoid confusion of what samples were tested. The first step was to place the 3% CNT tube between the top and bottom clamps of the Instron 3345. The distance of the clamps were adjusted with a control box. A piece of paper was rolled around the edges of the composite to disallow any increase of conductance cause by the metallic device. The clamps used relied on grip caused by friction due to the inability of the material to be bolted or glued. Therefore, they were well tightened. A multimeter was then connected using a clips lead set. The set was clipped on the copper plate tape over the silver line to obtain more accurate resistance. The multimeter was then connected to a PC, which would measure resistance per second during the test. A pre-load of 1N was applied on the sensor using a monitor. Once the load was applied, the test started with tension being applied on the sample. During the test for both computers recorded results. The computer attached to the multimeter recorded resistance, while the other PC recorded stress and strain. Unlike the first test, the experiment did not contain any pauses and was only stopped once the material snapped from failure. Once the material failed and all recordings were saved and stored, the next sample was then ready for testing. All samples for both 3% and 5% CNT followed the same procedure in testing. It was noticed that all samples failed at random areas along its length. All data was then safely stored onto a USB drive for later testing in the results section.

Figure 7: Tubed shaped composite sensor.

Results

The results obtained from the lab are shown below including plots of resistance/ displacement, stress/strain, and electric conductivity. Resistance was measured in Ohms and Kilo Ohms, while displacement was measured in (mm).

Tensile test of the composites coated on an aluminium plate

All points shown in the tables below are demonstrated in figure 6 to show their location in the coated material.

Table 1: Resistance in Ohms (Ω) for all three sensors before tension was applied.

POINTS	RESISTANCE (Ω)		
	3% (2mm)	5% (2mm)	5% (1mm)
1 – 5	76.1	27.6	67
2 – 6	74.5	0.5	58.7
3 – 7	73.9	26.5	44.9
4 – 8	105	33.8	51.4
5 – 9	91.8	52.5	74.5
6 – 10	64	41.1	56.9
7 – 11	62.3	41.1	50.3
8 – 12	92.5	51.2	58.2
9 – 13	85	33.5	62.2
10 – 14	77.4	30	41.9
11 – 15	72.8	29.5	43
12 – 16	83.6	41.4	55.7

The results in (Table 1) show and compare the resistance that each composite sensor contained when tested with a multimeter. The displayed results show that the resistance at all 16 points at 3% CNT were higher than 5% CNT. However, comparing both 5% CNT samples, the thinner coating material layer (1mm) had greater resistance than the 2mm thick layer. Another observation which was noticed was that members (5-9) for both aluminium plates containing 5% CNT had the

greatest resistance of 52.5 Ω and 74.5 Ω respectively. The members containing the highest resistance for 3% CNT were (4-8) with a value of 105 Ω. Close to the value were members (5-9) with a measurement of 91.8 Ω. One odd measurement spotted during the testing of 5% CNT with a 2mm thick coating material was at members 2-6. The measurement outcome was 0.5 Ω.

Table 2: 2mm 3% CNT's change in resistance caused when the aluminium plate was in tension.

POINTS	RESISTANCE (KΩ)					
	3% (2mm)					
	1	2	3	4	5	6
1 - 5	109.2	320.5	334	104	134	189
2 - 6	89.6	238.2	346	343.2	-	272
3 - 7	80.1	120.1	159	174.5	240	392
4 - 8	132.1	130.2	190	236.5	276	272
5 - 9	114.2	120.1	222	140.9	248	297
6 - 10	85.7	341	336	337	-	136
7 - 11	84.2	126	160	334	158	187
8 - 12	111.4	135	206	314	-	-
9 - 13	92.7	314	270	277	273	-
10 - 14	87.4	94	69	140	-	-
11 - 15	82.6	127	185	358	218	303
12 - 16	91.6	109	123	182.4	-	206

When the aluminium plate was put under tension, the energy harvesting material's resistance started to grow as displacement increased. The collected data at 3% CNT contained a larger resistance than the collected data at 5% CNT samples, where it was measured using (kΩ) rather than (Ω). Table 2 shows that the resistance kept on increasing up to the third pause. However, from the fourth pause the measurements of resistance started to get inconsistent. Some specific dots did not initiate any resistance starting from the fifth pause. Members 2-6, 6-10, 8-12, 10-14, and 12-16 did not gain resistance in the fifth pause. On the sixth pause, members 6-10 and 12-16 regained conductivity. However, members 8 - 12, and 10 - 14 did not regain any resistance, which was lost during the tension process. Table 2 also demonstrates that members 9-13 lost their resistance generation in the sixth pause. It was determined from Table 2 that there were no leading members containing the highest resistance throughout the test. In the first pause members 4 - 8 had the greatest resistance. However, from the second pause, the results started to scatter with different members containing the highest resistance at different points. For example at the second pause, members 1-5 had the highest resistance, while at the third pause the highest members in resistance were 2-6.

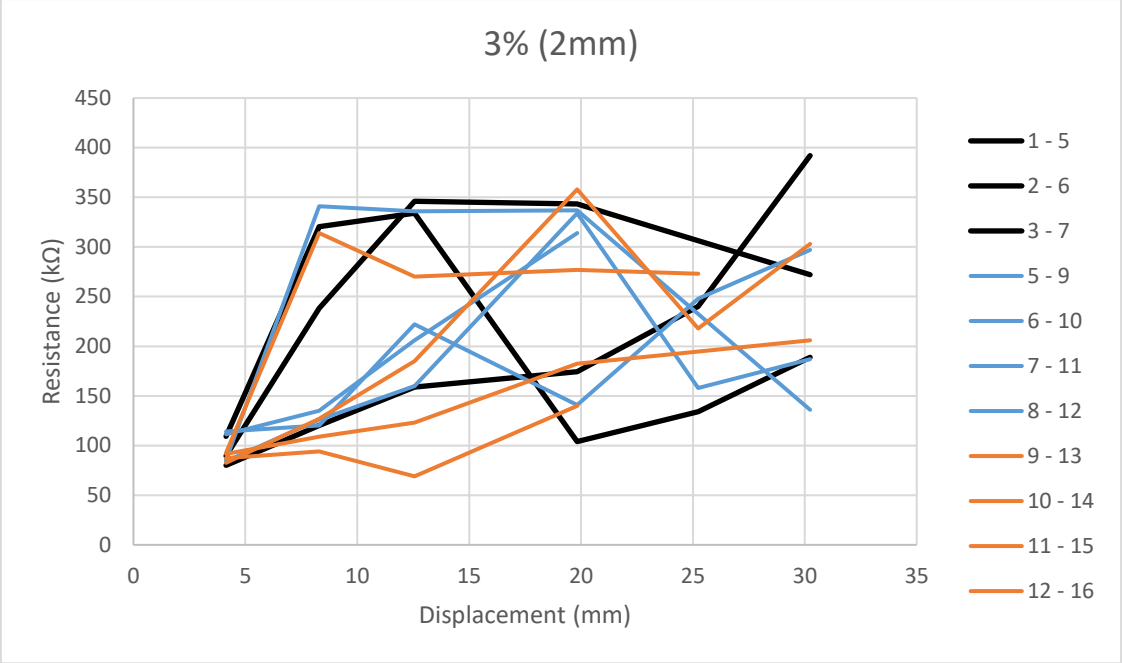

Figure 8: Resistance/Displacement values 3% (2mm) CNT/PDMS.

Figure 8 demonstrates how the coating material reacted when tensile force was applied with respect to resistance, causing the compact tension aluminium plate to increase in displacement between the machined notch where the pre-crack was made. The results showed that all members resistance increased in the first pause except members 4-8 where a slight amount of resistance reduced which might be caused by errors in resistance reading. As shown, the results then started scatter without a trend being created. The highest resistance obtained was from members 3-7 with a resistance of 392 kΩ. Additionally the lowest value was 69 kΩ conducted by members 10-14.

Table 3: 2mm 5% CNT's change in resistance caused when the aluminium plate was in tension.

POINTS	RESISTANCE (Ω)					
	5% (2mm)					
	1	**2**	**3**	**4**	**5**	**6**
1 - 5	30.6	36	47	68	151	105
2 - 6	1.1	1.7	2.5	6	46	13
3 - 7	28.7	33.9	37	45	46	59
4 - 8	35.8	38.5	41	46	50	61
5 - 9	70.1	123.5	220	306	-	-
6 - 10	57.6	80.5	119	320	-	-
7 - 11	46	60	86	113	200	-
8 - 12	54.1	61	73.5	99	114	200
9 - 13	40.3	77.5	142	-	-	-
10 - 14	43.5	78.1	117	-	-	-
11 - 15	32.4	48.3	65	92	-	-
12 - 16	43.2	46.8	50	58	98	305

Similar to 3% CNT, the 2mm thick 5% CNT coating material's resistance increased with the increase of displacement causing the material to stretch. As table 3 displays, points 5 – 9 and 6 – 10 had a great rise in resistance 306Ω and 320Ω respectively due to the fact they were located in the centre of the plate where maximum displacement occurred. However, both members did not obtain any resistance in the fifth and sixth pause with the last reading occurring at the fourth pause. It was detected from table 3 that members 9 - 13 and 10 - 14 did not gain any resistance at the fourth pause, which occurred one pause prior than 3% CNT. From pause 5 to 6, five pair members did not gain any resistance. As shown and compared to other points, members 2 – 6 produced little resistance. It contained a resistance of 0.5 ω before testing. It then gained more resistance when put under tension up to pause 5. However, resistance started to reduce once again by pause 6.

Figure 9 presents the resistance of the CNT/PDMS sensor composite hybridised on a compact tension specimen. As shown in figure 9, a trend was created. With each pause, resistance increased. Resistance of members located with a blue line in the plot demonstrated a great rise in resistance earlier than the edge members in orange and black due to their position being in the centre of the specimen where displacement is most effective. Members 5-9 located directly above the machined notch raised in resistance the fastest, with an increase of 52.5Ω initial resistance to 70.1Ω in pause 1. Following was members 6-10 which contained the highest resistance in pause 6. The edge members steadily increased in resistance making a trend. However, members 12-16 resistance increased rapidly in a space of two pauses.

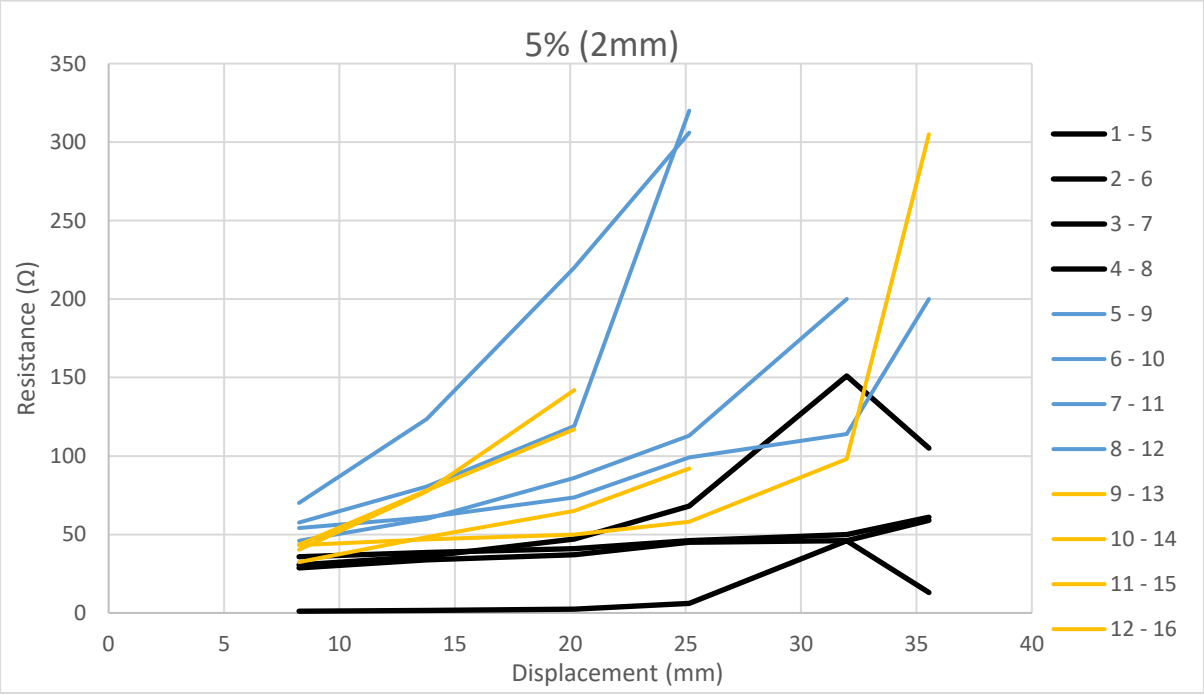

Figure 9: Resistance/Displacement values 5% (2mm) CNT/PDMS.

Table 4 demonstrates the resistance contained by the points. Members 5 – 9 and 9 – 13 contained the highest resistance in the material through all six pauses. It was noticed that 5% CNT with 1mm thickness was the most affective material in terms of obtaining resistance. Table 4 demonstrates that only members 9 – 13 could not gain resistance at the sixth pause. It was also noticed that from the first to the last pause, all values increased at a good state with some minor inconsistencies occurring to different members at different pauses. An example from what was demonstrated would be: members 3 – 7 had a resistance of 53.1Ω at pause 4. It then reduced to 52.4 Ω at pause 5 while increasing to 57.2 Ω by pause 6. The errors were minor, meaning that they might have been caused by human error such as inaccurate measuring.

Table 4: 1mm 5% CNT's change in resistance caused when the aluminium plate was in tension.

POINTS	**RESISTANCE (Ω)**					
	5% (1mm)					
	1	**2**	**3**	**4**	**5**	**6**
1 - 5	68.5	74.1	78.9	81.1	104.1	340.1
2 - 6	59.8	66	69.4	70.1	72.1	106.2
3 - 7	45.5	49.5	52.1	53.1	52.4	57.2
4 - 8	51.7	54.3	59.4	55.6	56.9	57.3
5 - 9	79.4	113.1	242.4	306.1	285.1	411.1
6 - 10	59.5	76.8	150.3	162.1	203.2	251.3
7 - 11	51.4	56.8	65.1	72.2	80.2	81.3
8 - 12	86.6	64	71.2	88.1	98.2	103.9
9 - 13	62.2	77.6	250.1	361.2	303.2	-
10 - 14	42.7	54.3	81.8	111.2	140.1	244.3
11 - 15	45	49.1	52	58.2	72.2	211.5
12 - 16	56.2	59.3	62.7	73.9	95.4	194.3

Similar to figure 9, Figure 10 demonstrates the increase of resistance when the aluminium plate was put in tension. Figure 10 similarly shows a trend developed with the increase of resistance. The highest resistance recorded was 411 Ω at points 9 -11 with a displacement of 79.6 mm. It was observed that the 1mm thick coating material produced a larger resistance than the 2mm 5% CNT. Similar to Figure 9, members located in the centre of the compact tension specimen produced a high average of resistance. However, the members plotted in orange where noticeably high.

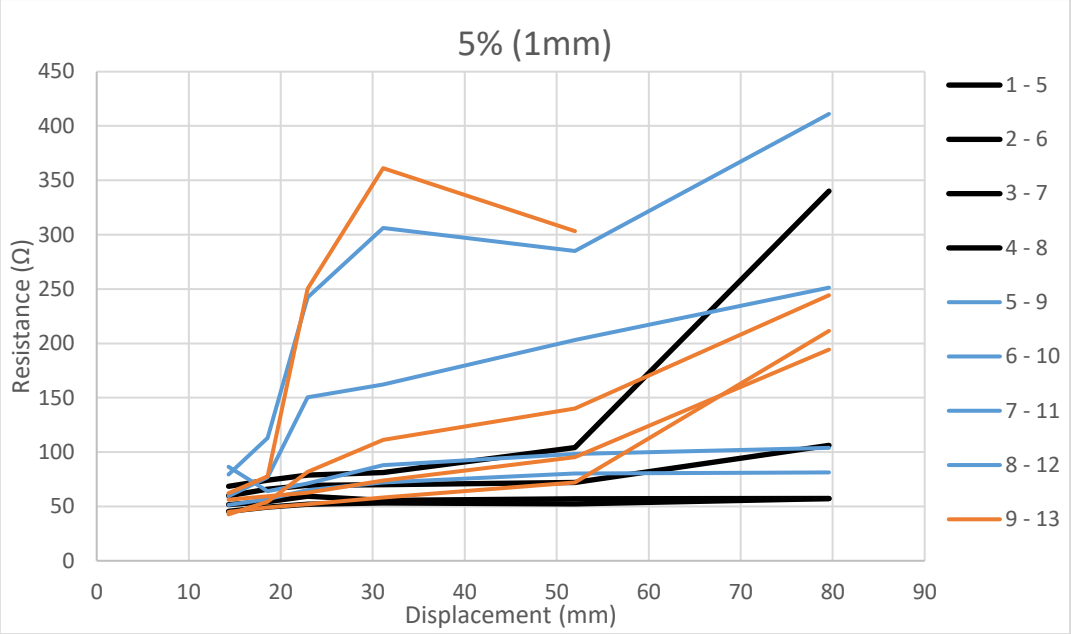

Figure 10: Resistance/Displacement values 5% (1mm) CNT/PDMS

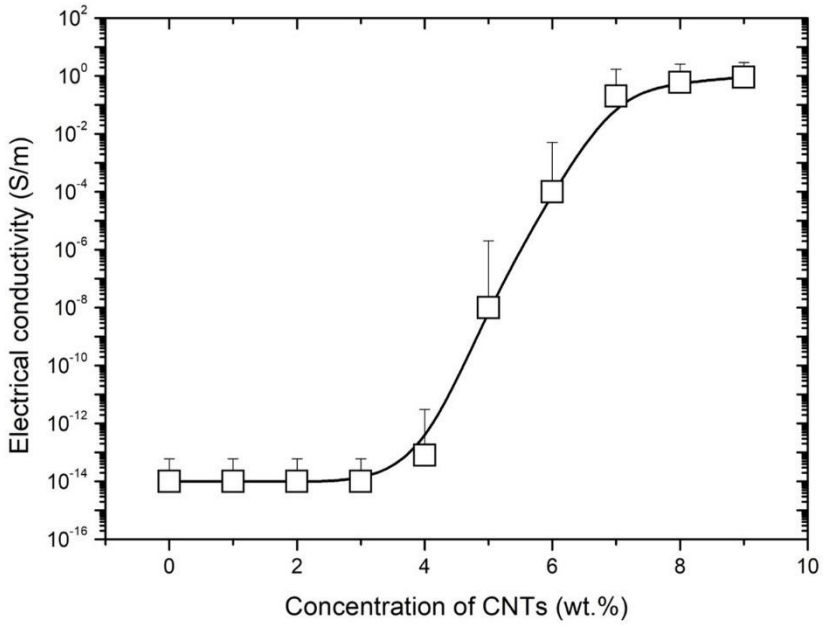

Figure 11: Electronic conductivity with respect to % of CNT Jang and Yin (2015).

Figure 11 demonstrates different values of electrical conductivity with respect to the weight percentage of CNT in the material. The figure shows that the higher the percentage of CNT added in the polymer, the greater electrical conductivity it produces. Conductivity was therefore calculated using the formula below:

$\sigma = \frac{L}{RA}$ → measured in Siemens per meter (S/m)

L= length between two inner electrodes → $6.88 \times 10^{-7} m$

A= area of the composite → $0.05 \times 0.05 = 2.5 \times 10^{-3} m^2$

R= resistance of the composite (Depending on the members and CNT%)

An example to calculate conductivity of 5% CNT (1mm) thick is shown below:

$\sigma = \frac{6.88\times10^{-7}}{2.5\times10^{-3}\times74.4} = 3.69 \times 10^{-6}\ S/m$ → The result demonstrates a similar value to Jang and Yin (2015) where 5% CNT contains an electrical conductivity ranging between $\times10^{-8}$ S/m to approximately $\times10^{-5}$ S/m.

Tensile test on tube shaped composites

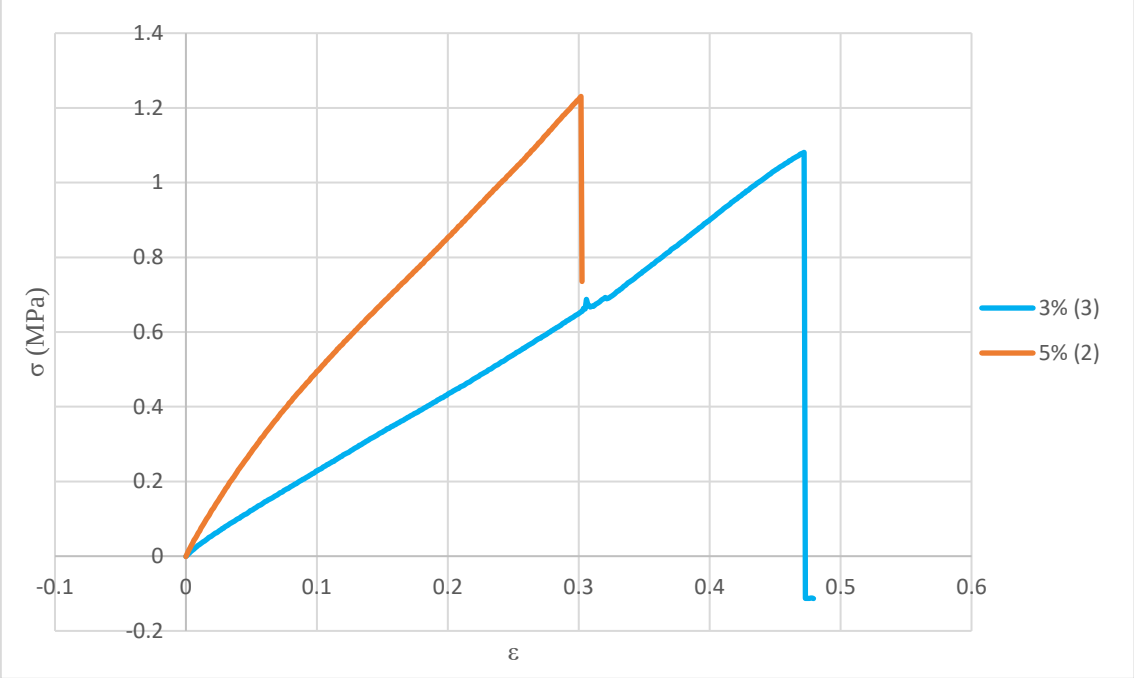

Figure 12: Stress/Strain of a 3% CNT sample against 5% CNT.

Figure 12 demonstrates a stress/strain graph between to different samples containing different CNT weight percentages. The results demonstrate 5% CNT containing higher stress values than 3% CNT. It was also observed that 5% CNT failed before 3% CNT due to the material being more brittle. The 3% CNT sample took longer to fail due to the ductility of the material.

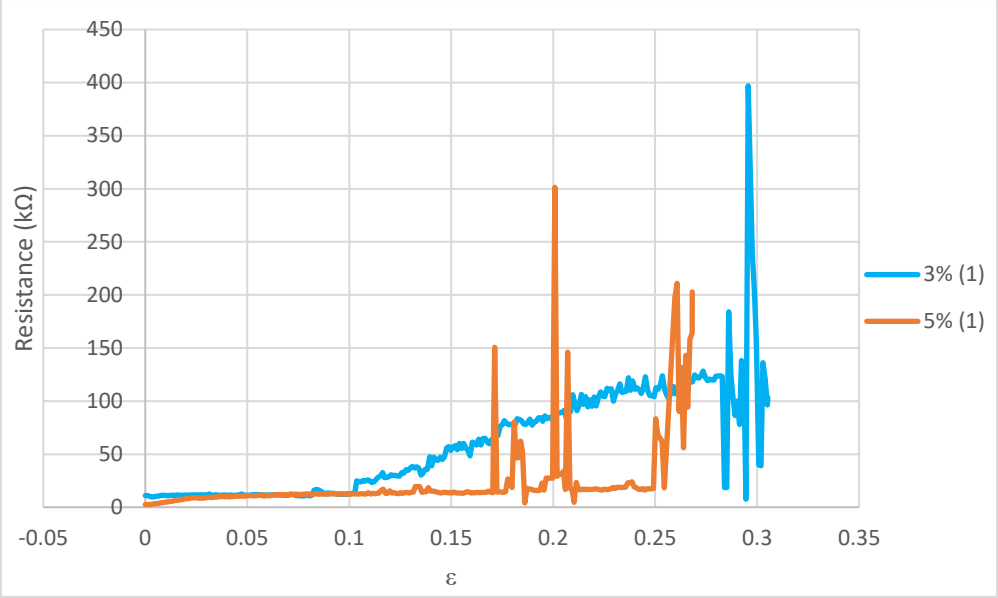

Figure 13: Change in resistance with the increase of strain.

Figure 13 demonstrates the change in resistance when tension was applied. Strain was calculated by the change in length divided by the samples original length. 3% (1) contained a greater resistance than 5% (1). Additionally, it contained a better trend, whereas 5% (1) resistance started to scatter early in the test.

Discussion

The aim of the experiment was to introduce nano-technology or more specifically, nano-sensors to the civil engineering field, due to the noticeable amount of energy wasted from civil structures such as roads, bridges, and beams. If such energy is collected, it can be used for different uses such as, traffic monitoring, structure behaviour monitoring, and security. Two different experiments were conducted to test whether nanosensors can be used in the civil engineering field. In the first experiment, three composite sensors were fabricated. Each contained a specific weight percentage of CNT in relation to PDMS 2%, 3%, 5%. The material was then coated on a compact tension specimen containing either 1mm or 2mm thick material. The objective was to test the hybrid in tension and measure the resistance created by the material. The results were then recorded and analysed.The second tests aim was to determine the strength and ductility of the material. The composite was fabricated and coated in a silicone tray to get a tube shape. The samples were then tested on their tensile strength. Stress and strain were then recorded from tension

The first observation noticed while measuring the initial resistance was that 2% CNT did not provide any resistance. The material was not conductive due a small amount of CNT compared to PDMS which is a non-conductive material. Therefore, no proceeded test was done on it. It was noted when the initial resistance measurements of 3% and 5% CNT samples were recorded, 3% CNT contained a greater resistance. The weight percentage ratio of 3% CNT was the reason of high resistance. PDMS is naturally a non-conductive material. However, when dispersed with CNT, it became a conductive material due to the great electrical conductivity

abilities of CNT. Nevertheless, the weight ratio of PDMS compared to CNT was large, causing the CNT to be further apart, which consequently initiated high resistance.

Two samples of 5% CNT with different thicknesses were measured for resistance. The initial recorded values showed that the 1mm thick coating material provided greater resistance than the 2mm thick material. A reason could be due to the way the CNT was distributed in the PDMS polymer. However, both 5% CNT samples contained a lower resistance than 3% CNT. The reason is due to the percentage of CNT added to the PDMS which makes the material more conductive. Kim et al. (2018) similarly demonstrate in their research, that the lower the percentages of CNT contained in a PDMS polymer, the higher the resistance was obtained.

One odd recorded result noticed in Table 1 was in members 2-6 in the 2mm thick 5% CNT sample. The resistance obtained was 0.5Ω. The result was relatively low in comparison to the other two samples. A reasonable result could have been in the range of 20 to 40 Ohms as an average obtained from other members around it. It was an obvious indication that a fault has occurred. Multiple efforts have been made to obtain a better resistant by applying the probes of the multimeter in different parts of the silver paint above the composite. However, there was no sign of improved resistance. A possible fault, which could have caused this error to occur, was fabrication. When the coating material was flattened, there could have been inconsistencies in the amount of CNT located in the specific area.

During the experimental process, three specimens were tested in tension to record the resistance generated by the composites. The first test was on the Hybrid containing the 3% CNT composite coated on a compact tension aluminium sample. As Table 2 and Figure 8 indicate, the resistance increased when tension was applied on it. For example, members 1-5 increased from 76.1 Ω to 109.2 kΩ in the first pause, increasing up to 334Ω in the third pause. The increase of resistivity was due to the increase of the engineered notch displacement. Resistance then decreased on the fourth pause. A possible reason could be due to slight faults in fabrication or errors in resistance measurement. Resistance was measured using a positive and negative probe connected to the multimeter. The measurements were taken approximately due to resistance changing from slightest movements and pressure being applied on it. Proof of slight inaccuracy was that readings then increased in the next two readings. One example measurement from members located in the centre of the aluminium plate are members 6-10. Similar to members 1-5, resistance increased with the increase of displacement caused by tension. In pause 1, resistance increased from an initial resistance of 64Ω to 85.7Ω. Resistance then increased drastically due to the material being located in the centre of the specimen where displacement was most effective. For example, in pause 2, resistance increased from 85.7Ω to 341Ω. It was also noticed that from the fifth pause some members did not generate any resistance. A possible reason could be while the material was stretched and measurements were taken the probes could have caused small holes or scratches in the material. Another observation made was that if specific members like (8-12) did not generate resistance, the members parallel to it like members (12-16) did not generate resistance either. That could be due to member 12 not generating any resistance which affected member 8 and 16. Another example were members 2-6, similarly affecting members 6-10 which later affected

members 10-14 in resistance initiating in pause 4. The most probable reasons of the results being scattered in Figure 8 was due to fabrication or measurement errors.

The second test conducted was on 5% CNT with a 2mm thick coating material. Similar to 3%, the specimen was tested in tension. The highest measurements recorded were located in the centre with a maximum resistance of 320 Ω at members 6-10 shown in Figure 9 and table 3 due to their location being in the centre of the specimen where displacement was critical. Figure 9 demonstrates a trend that occurred at all members where resistance was increasing steadily. It shows a much better correlation than 3% CNT in Figure 8. Even with the application of tension, members 2-6 contained very low resistance compared to the other members. When displacement reached about 32mm in the fifth pause, resistance increased from 6Ω to 46Ω which might have been the composite getting stretched causing the CNT in that position to get an improved alignment. Compared to 2mm 3% CNT, more members in 5% CNT lost their resistance starting from the fourth pause. However, could not regain resistance after losing it. A possible reason could be due to the extra CNT in the 5% sample compared to 3%. The increase of CNT weight percentage made the sensor less ductile, which could have caused failure if stretched over its yield limit in a specific location.

To test whether Opoku et al. (2015) statement of a thinner coating material containing the same amount of CNT to the previous experiment would be more flexible and durable, a 5% CNT/PDMS (1mm) sensor was made. Figure 10 and Table 4 demonstrate that resistance of the 5% CNT (1mm) thick sample. Resistance increased steadily with each pause other than members 5-9 and 9-13, which increased drastically from the start. The location of members 5-9 could have been the reason of such high resistance, which could have caused member 9-13 to react similarly due to the shared member 9, which already contained a high resistance. Figure 10 demonstrates a trend that was formed with the increase of displacement resistance increased. The highest recorded data shown in Figure 10 was in members (5-9) with a resistance of 411.1Ω. Comparing 5% (1mm) CNT with the two other samples, Table 4 demonstrates that only one member (9-13) could not provide resistance, which was in the sixth pause. However, the 2mm coating material samples lost resistance in more members. Therefore, as per Opoku et al. (2015) stated, a reason could be due to the thickness of the samples, where the thinner coating material was more durable and ductile than the thicker materials. Another reason could be when measurements were taken, the probes did not go through or affect the material as it could have in the previous tests due to its ductility.

Figure 11 demonstrates different weight percentages of CNT in relation to PDMS. It shows that the more CNT was added to the composite, the higher the electrical conductivity results were. An observation was made regarding the relationship of electrical conductivity and the materials resistance. It was noticed that the higher the CNT percentage was, the lower the resistance (Ω) it contained. Consequently, affecting electrical conductivity with higher results. Electric conductivity of 5% CNT was then calculated with the results obtained from the experiment. Electrical conductivity was therefore equal $\sigma = 3.69 \times 10^{-6}$ S/m. The result obtained laid in the range given in the graph by Jang and Yin (2015), which was between $\times 10^{-8}$ to approximately $\times 10^{-5}$. The results found were positive with the sensors achieving their expected electrical conductivity.

One important observation noticed while in testing was that all samples started to deflect and bend with the increase of tension applied on them. Another observation was that the growing crack did not have a straight path through the specimen. The crack behaved in a curve shape as shown in Figure 14. The reason for the specimen to fail and bend was due to its material being ductile. Another reason which could be a possibility was the dimensions of the specimen. The compact tension specimen was cut to specifications according to a previous sample made in the lab. However, there are standard specimen dimensions which are given from organisations such as ISO and ASTM. Difference in dimensions could affect how the CT specimen acts when in tension.

To test whether a more brittle material would improve the result, a quick test was conducted on a titanium compact tension specimen. Using the same equipment, tension was applied. Results demonstrated that a more brittle material showed improvement in the materials bending and crack path. A significant reduction in the specimens bending was observed. Additionally the crack had a straighter path with no great curve occurring.

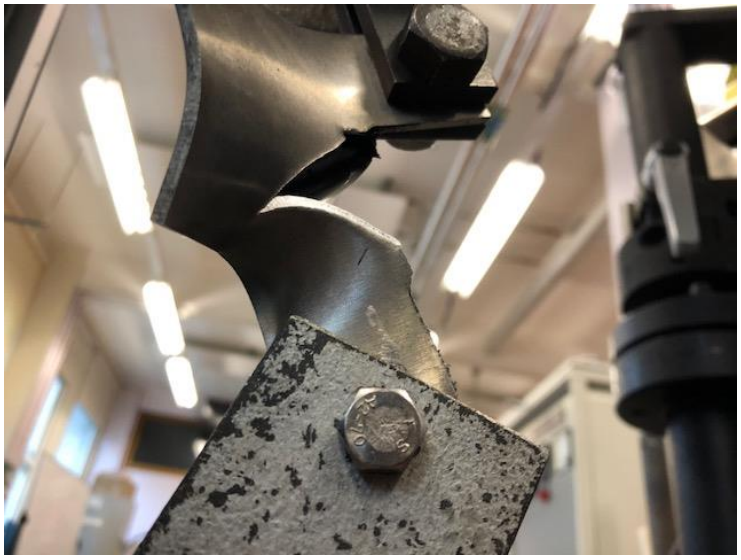

Figure 14: Crack behaviour on the aluminium sample.

Figure 12 demonstrates the stress/strain test conducted between 3% and 5% CNT. The results demonstrate that the strain in 5% CNT is lower than in 3% CNT due to it being a less ductile material. Accordingly, Figure 12 shows that the 5% sample tended to fail and snap earlier than the 3% sample. Additionally, 3% CNT sample tended to stretch more than 5% CNT due to it containing less CNT in the mixture making it more ductile. 5% CNT reached a yield strength of 1.22 MPa while 3% equalled 1.07 MPa.

Figure 13 demonstrates the change in resistance against strain. When the material stretched, it gained more resistance. Figure 13 shows that 3% CNT had contained higher resistance than the 5% CNT, due to 3% CNT being less conductive. However, 3% CNT developed a trend in the increase of resistance, whereas 5% results started to scatter. Therefore, it was noticed when the sensors were stretched, the CNT particles expanded away from each other causing additional resistance for all CNT percentages. However, the difference was in ductility where 5% CNT failed earlier than 3% CNT meaning the extra CNT percentage caused the material to be less

elastic therefore it deteriorated and failed easier than the 3% CNT when tensile stress was applied on it.

Conclusion

The aim of the experiment was to test nano-sensors, one type of nano-technology to increase the understanding of whether they can be applied effectively in the civil engineering field. Nano technology can be applied in different ways. However, a decision was made to create a coating material, which will be used as a sensor to monitor structures. Multi-walled CNT was used as the conductive material due to its great electric conductivity. PDMS was used as a polymer due to its great mechanical properties. The mixture was then dispersed with Acetone as a solvent. To test what was the ideal solution to use for later practises, three CT specimen were created. For the first test, two composite sensors with different CNT weight percentages of 3% and 5% were fabricated and coated on the CT specimen with a thickness of 2mm. The third sample contained 5% CNT. However, a thickness of 1mm was coated on the CT specimen to test difference in ductility. The samples were later tested in tension. The materials ductility was later tested in a second test were tension was applied on the samples up to failure.

Three different outcomes were revealed in terms of resistance and electric conductivity. 3% CNT contained the highest resistance from all three samples. When the specimen was put under tension, resistance of the 3% CNT increased drastically that resistance was later recorded in kilo Ohms (kΩ). Additionally, few members started to lose their resistance when in tension. 5% CNT 2mm had a good correlation with resistance increasing with the increase of displacement in the CT specimen. However, similar to 3% CNT resistance at some members in the composite started to lose their resistance. 5% CNT 1mm thickness contained the better results compared to the other samples. Resistance increased in a trend shape with the increase of displacement. Unlike the former samples, 5% CNT 1mm only lost resistance at one member.

Six tube shaped composites containing both 3% and 5% CNT were tested in tension to examine their strength. 5% CNT withstood larger stresses however, its resistance readings were changing drastically causing huge inaccuracy. 3% CNT contained better readings with an increasing trend forming, due to the material being able to withstand the a higher amount of stress applied on it in the tensile test. The 5% CNT due to it being less ductile snapped earlier with visible failure occurring to the material before snapping.

It was determined that the best solution from the initial experiment was 5% CNT with a 1mm thickness. It showed a good amount of ductility, resistance, and electric conductivity. Due to it being thinner than the 2mm 5% CNT sample, it was more ductile while the extra CNT percentage provided it an advantage to be more conductive. Therefore, it was conducted that thickness as well as CNT% were important factors in determining the best product. All three samples reached their expected electrical conductivity meaning that they can be used as sensors in different applications. Relating the experiment with civil applications, the sensors created can be used to monitor deflections in beams. When deflection occurs, it will increase the amount of resistance in the sensor causing the monitor to generate a warning, which can later be checked by an engineering team if extra attention is

needed. Another use of the sensors would be to monitor cracks that could occur in a bridge or building using the same way to monitor the failures.

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