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Eddy Current Inspection-based Damage Detection of Carbon Fiber Reinforced Polymer Composites

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Abstract— Carbon fiber-reinforced polymer composite is used in various industries such as aerospace, automobile, and civil engineering. During the manufacturing stage and end-user stage, carbon fiber composite material is subjected to different kinds of damage, such as delamination, de-bonding, and fiber breakages. Those damages may lead to destroying the application with a life-threatening catastrophe. To identify these kinds of damages, several non-destructive testing (NDT) techniques are used, such as visual, ultrasonic, and optical fiber sensing. However, when considering the initiation and propagation of the damage, microlevel and invisible cracks are crucial. This study used plain weave carbon fiber fabric with an appropriate resin-hardener mixture to make carbon fiber-reinforced composite sheets by hand layer-up process. Subsequently, the samples were subjected to drop weight impact tests with 0.6 j, 1.2 j, 3.0 j, 6.0 j, and hammer impact tests respectively. By using an Ectane-2 eddy current inspection equipment, both sides of the carbon fiber samples were scanned before and after the impact damage. The defect’s location could be seen on the c-scan plane, while the crack propagation could be seen on the impedance plane of the Ectane-2-magnify software screen. Variations in voltage showed an irregular pattern on the impedance plane because of the damage to the carbon fiber strips that affected the electrical conductivity of the composite. The eddy current inspection method is capable of identifying the damage location and propagation of plain weave carbon fiber-reinforced polymer composites. In the future, fiber weaves such as twill and unidirectional need to be investigated.

Keywords: Carbon fiber (CF), Composite materials, Eddy current, Non-destructive technology (NDT), Woven fabrics

1 Introduction

The composite material is known as a combination of two or more materials with different physical and chemical properties [1]. Humans have used and still have been using composite materials for thousands of years in different areas. The materials are subjected to various kinds of forces due to physical and chemical effects. So, damage might be occurred. For the investigation of those damages there are various kinds of Non-destructive inspection methods such as Liquid Penetrant Testing, Ultrasonic Inspection method and Visual Inspection. Eddy Current Inspection method is one of the most accurate and trustable inspection methods in the modern world [2]. With the electromagnetic principle [3], it can be found surface and near surface defects with very accurate details in conductive materials that cannot be seen visually. This method is used in various kind of industries such as automobile and aerospace, but very rarely used in Sri Lanka because this method is a high-cost method with comparing to Liquid Penetrant and Ultrasonic Inspection Method.

1.1 Background of the research

The Eddy current inspection method (ETC) is used for the damage detection in Carbon fiber reinforced polymer composite material [4]. Carbon fiber reinforced polymer composite is also a composite material that has been made by humans [5] to produce stronger modern applications for the developing global wants with good mechanical and structural properties. This material was also used for the “Vega” Car in Sri Lanka [6], but with comparing to other material it is high-cost material. But the strength is very high. With the primary purpose of detecting the defects on carbon fiber reinforced composite material such as delamination [7] and fiber breakages, the manufacturing faults and the failures in deferent impact scenarios were detected using the Eddy current inspection method. Then the obtained data were analyzed to predict the physical properties in Carbon Fiber Reinforced composite material.

2 MATERIALS AND METHODS

The materials used for the research activity can be classified as shown in the Table 1.

Table 1. The materials used for the research experiment

Material	Quantity	Description
CF woven fabric	1	200 gsm plain weave (18” × 8”)
Resin	1	TR-8200 O-phthalate marine resin
Hardener	1	MEKP Hardener
Glass-plate	1	Cleaned glass plate
Nonstick sticker	1	With the dimension of 10” × 10”
Masking tapes	1	For the prevention of any movements of the CF fabric
Eddy current Inspection Machine	1	Ectane 2 - Eddyfi, Eddy current inspection machine with flexible array probe
Laptop with Magnifi 4.8r20 Software	1	To observe the results and regulate
Oven	1	For the post curing process
Brush and wooden roller	1	For the process of compacting

Mainly Carbon Fiber 200gsm plain woven fabric was used with TR-8200 O-phthalate marine resin and MEKP Hardener to prepare the samples. The Ectane 2 Eddy current inspection machine was used with flexible array probe along with calibrations to detect damages and other miscellaneous tools and accessories were used as shown in the Table 1.

The research methodology followed during the research activity is shown in Fig. 1.

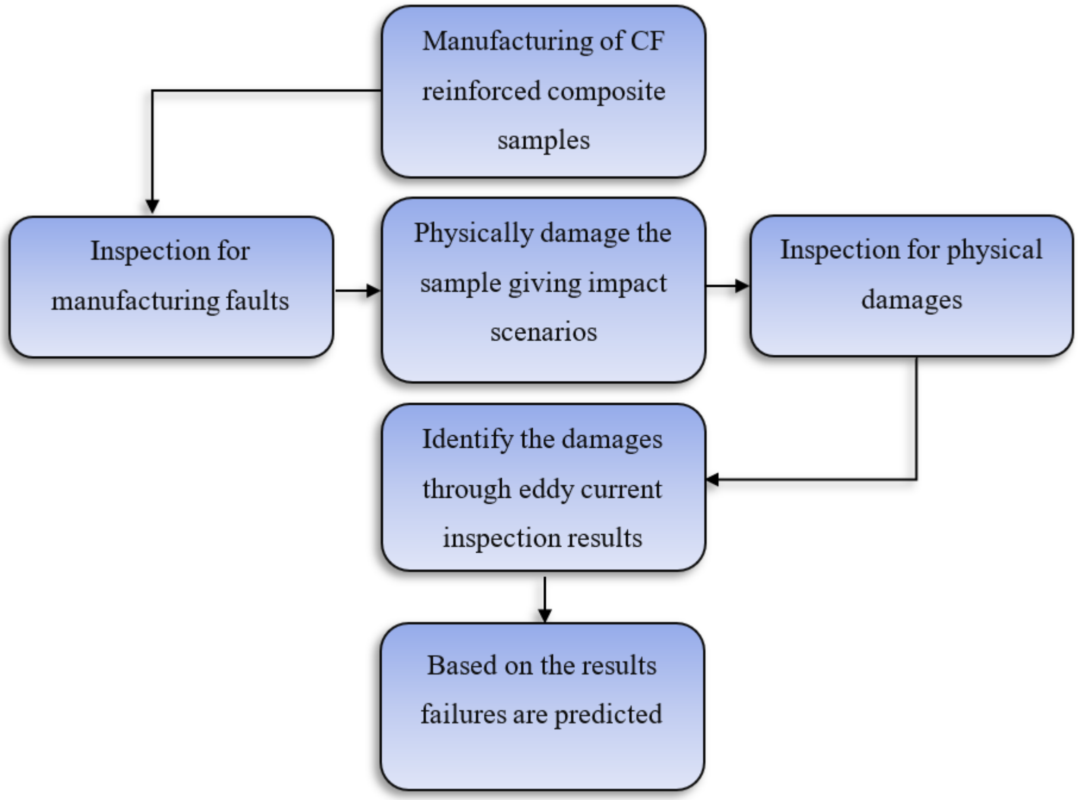


Fig. 1. The research methodology from manufacturing to investigating the defects on carbon fiber reinforced polymer composite samples

2.1 Sample preparation

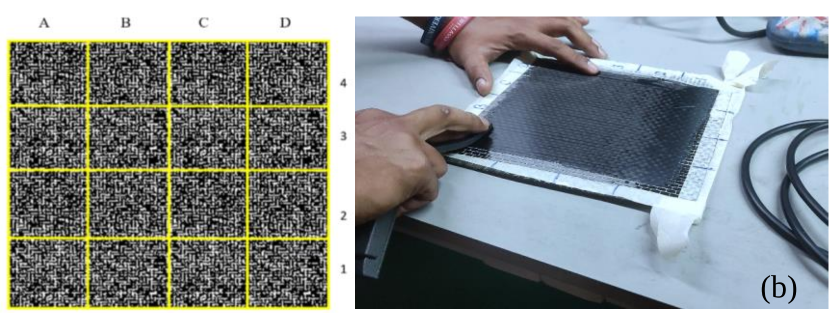
A, 18” × 8” carbon fiber (CF) 200 gsm, plain woven fabric was used and was cut in to three layers of 8” × 6” measurements. TR-8200 O-phthalate marine resin was used with NEKP hardener [8], to make the adherence for the sample preparation, because of good water resistance and mechanical strength. According to the ambient temperature, the required mixer must have been obtained such as when the room temperature is around 25 °C; resin is taken 100 ml and the harden is used around 5 ml. When the experiment was being done, the room temperature was around 25 °C, then this mixture could be used. (If the room temperature lies between 28 – 30 °C, resin is used 100 ml while harden is used 3 ml respectively). First, the glass plate was cleaned using acetone (C_3H_6O) and the non-stick sticker was stuck on the cleaned glass plate and the 1st CF layer was placed on it. The resin and hardener mixer were coated on the CF 1st layer gradually with a 1-inch width brush and a roller. Then the 2nd layer was placed on the 1st layer and again the resin-hardener mixer was applied on it. To keep the layers without shaking and moving, masking tapes were used to tightly stick them onto the glass plate. As same as the final layer was placed to get the required thickness of 2mm. Then the sample was kept at normal ambient temperature for 24 hours. After 24 hours the sample was subjected to the post curing process at 60 °C for 60 minutes and 80 °C for 60 minutes consecutively [9].

2.2 Experimental stages

The Ectane 2 Eddy current inspection machine was used with the "**Magnifi"** software, and the following settings were used to setup the machine before the experiment [10].

- Surface geometry was used with generic application.
- Carbon fiber sample.
  - Resistivity : 21µΩ.cm
  - Permeability : 400µ
  - Velocity : 5890.000 m/s
- Surface thickness: 0.73mm
- Width (X size) : 139.7mm
- Length (Y size) : 191mm
- Single pass scan was implemented.
- Both X and Y axis offset 0.000mm is used.
- Main scan axis : X axis
- Position form : Clock
- Acquisition rate : 250Hz
- Typical probe speed : 15.0mm/s
- ECT, I-Flex – ECA-IFG-034-500-0048_Standard eddy current array probe, I – Flex^{TM} small with 3 different built-in topologies, 34mm (1.34in.) coverage, 500kHz central frequency, 48 coils offering up to 60 channels was used.
- Gain 32GB was used with F1 = 500kHz, Amplitude = 5.00V wile phase angle 0.0^{0}
- C - scan F1SDDA;
  - Palette : Inverted Symmetrical
  - Range : from -0.66V to 0.70V (In appendices page no:69; Color pallet change details)

After the post curing process, before detaching the sample from the glass plate, the well dried sample was taken for the preliminary scanning process to investigate the manufacturing defects and internal defects by Ectane 2 Eddy Current C-Scanning Process [11]. For the easiness of scanning process, the sample was marked and divided into 16 parts as shown in Fig. 2. a. After that the sample was detached from the glass plate and the other side of the sample was scanned also.

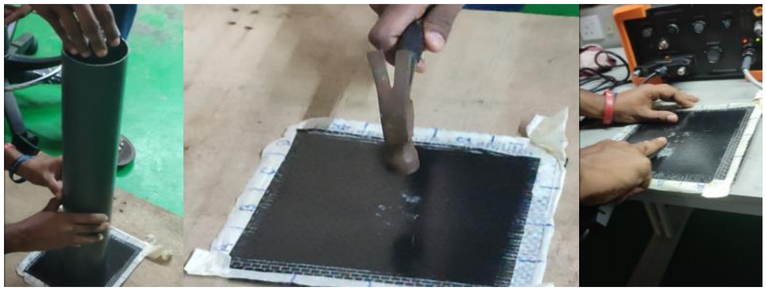
(a)


(b)

Fig. 2. (a) Divisions marked on the sample, (b) scanning the sample

A single pass scan was conducted as shown in Fig. 2. b. using the flexible array probe of ECA – IFG – 034 – 500 – 048 – N03S, along the main X axis under the clock position form. The acquisition rate was 250 Hz. The sample was scanned maintaining a typical probe speed of 15.00 mm/s.

As shown in Fig. 2. a. and b., for both sides of the sample, along with A, B, C, D directions, the probe was driven to check whether the availability of manufacturing defects. Along with 1, 2, 3, 4 directions the same procedure was conducted.



(a) (b) (c)

Fig. 3. (a) Drop weight impact damages, (b) hammer impact damages, (c) scanning on the impact damages

Table 2. Sequences of impact loads according to the desired heights

Test Number	Description	Gravitational Potential Energy ($PE_g = mgh$)
01	100g weight was dropped on to the CF sample with a height of 24 inch to make an impact damage.	100g×9.80665×0.6096 = 0.597813384 Nm / 0.6 Nm
02	200g weight was dropped on to the CF sample with a height of 24 inch to make an impact damage.	200g×9.80665×0.6096 = 1.195626768 Nm / 1.2 Nm
03	500g weight was dropped on to the CF sample with a height of 24 inch to make an impact damage.	500g×9.80665×0.6096 = 2.98906692 Nm / 3.0 Nm
04	1kg weight was dropped on to the CF sample with a height of 24 inch to make an impact damage.	1kg×9.80665×0.6096 = 5.97813384 Nm / 6.0 Nm
05	A hammer impact was given to the CF sample to make a crack.	
06	2nd hammer impact was given to the CF sample to make a crack.	
07	3nd hammer impact was given to the CF sample to make a crack.	
08	4nd hammer impact was given to the CF sample to make a crack.	

According to Table 2, after each and every impact damage on the CF sample was scanned by Eddy current inspection machine to investigate the crack propagation as shown in Fig. 3.

2.3 The method of analysis

The obtained data were used to analyze the defects on CF sample with the use of Magnifi software. Here both sides of the CF sample were scanned using eddy current array probe. To detect the manufacturing defects, the crack propagation and impedance angle with the voltage were measured and compared with the results obtained after the impact load scenarios as shown in Table 2. At 100g, 200g, 500g and 1kg the weights were dropped on the sample with the height of 24 inch respectively. After that, impact forces were given using a hammer until breaking down the CF sample making a visible crack on the surface and those damages were detected by eddy current inspection method simultaneously with the impact loads as shown in the Fig. 3. To identify the crack propagation clearly, a specific point (the most damaged spot) on the sample was selected and with that point further experimental observations and conceptions were continued. The changes in impedance plane were observed while C-Scan results were explored. According to the changes in the C-Scan plane and the Impedance plane the defect areas were identified.

3 RESULTS AND DISCUSSION

C- Scan and Impedance plane results in the initial stage before giving the impact damages as shown in Fig. 4.

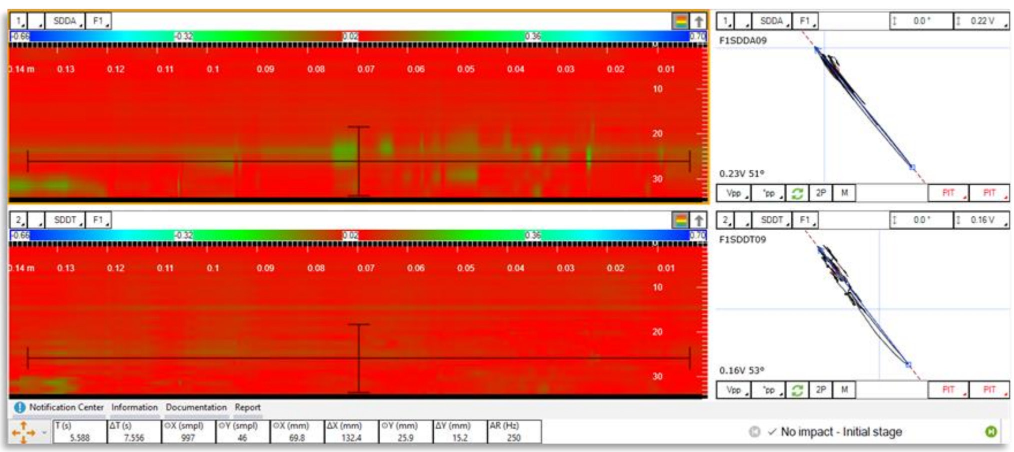


Fig. 4. C-Scan results of manufacturing defects

At the very beginning after making the sample, it was subjected for the experimental stage of manufacturing fault detection. As shown in Fig. 4. the manufacturing defects could be seen in green color with the red background area in C-Scan plane. The manufacturing failures clearly denoted not only in axial direction but also in transverse direction. At the initial stage the impedance plane angle was 51^0 in axial direction at the impedance voltage of 0.23V while 53^0 in transverse direction at the impedance voltage of 0.16V. With that angle, the crack propagation could be seen clearly in the impedance plane as well. These kinds of defects might occur due to delamination and matrix cracking effects. When the sample is manufactured, the CF fabric might have some voids in between CF woven strips or loosen braids in over under pattern of the woven. Since the CF material is a conductive material, conductivity barriers might occur for the eddy current loops generated while the scanning. Then the voids act as a barrier and considerable changes in the C-Scan plane show the shape of the defect as green areas. The impedance plane shows the behavior of crack propagation. Delamination effects may be occurred due to the loose compact of the layers, resin free areas, the mechanical status of the resin and hardener type, room temperature and cure temperature also might affect for the final quality of the CF sample and might occur conductivity barriers also. In here the sample has been made on a nonstick sticker without using air bags or vacuum pressures, the compact pressure on the CF sample was given manually with a wooden roller. Then the impact pressure variations might occur. Those variations could lead to a decrease in the final quality of the CF sample. The prepared sample was exposed to room temperature for 24 hours. Even during the room temperature, void bubbles might occur. Such kind of void bubbles cannot even be seen visually but might decrease the strength and only can be seen by these kind of NDT techniques.

3.1 Impact damage stage

To investigate the impact damage areas through Magnifi interface and for the easiness of future investigations a specific point was selected on the CF surface, because with the complexity of the impedance plane visualization and C-Scan visualizations, some small cracks cannot be identified visually. The C-scan indicates the shape of the crack while the impedance plane shows the impedance angle with the voltage values. CF material is conductive for both axial and transverse directions, then the impedance visualization was irregular to identify. The impedance angles and the voltage values with the impact loads have been shown in Table 3. According to the Axial and Transverse angles the Impedance voltage have variations even from the no impact stage. As explained previously, the sample has manufacturing damages also. So, the variation has been expanded with the increment of the impact loads.

Table 3. Impact damage C-scan and Impedance graph results

Test	Impedance angle		Impedance voltage (V)	
	Axial	Transverse	Axial	Transverse
No impact	51^0	53^0	0.23	0.16
100g	52^0	44^0	0.19	0.22
200g	51^0	50^0	0.10	0.02
500g	52^0	64^0	0.16	0.04
1kg	51^0	52^0	0.33	0.25
Hammer 1	51^0	47^0	0.16	0.05
Hammer 2	51^0	50^0	0.15	0.07

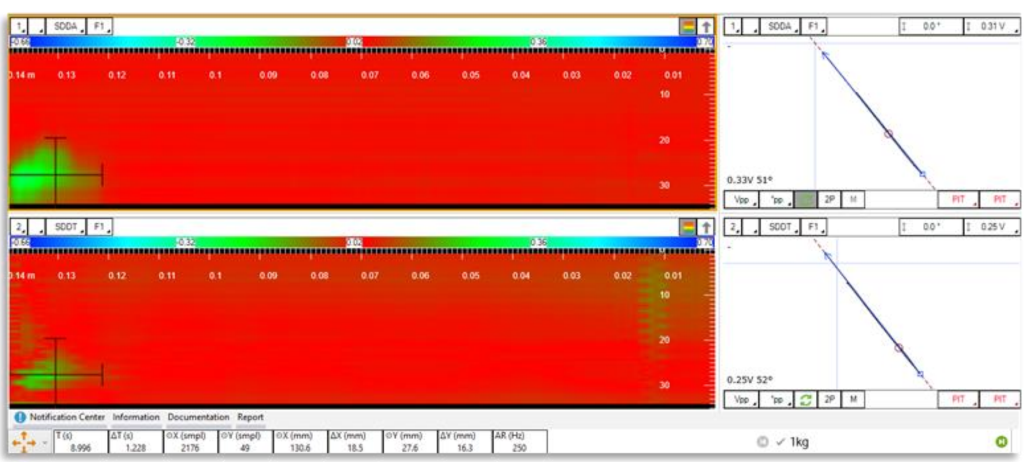


Fig. 5. The impact damage results of 6.0 Nm force

After giving the 1kg/6.0Nm impact load to the CF sample, a visible damage appeared on it. So, the crack could be seen clearly on the C-Scan plane as shown in Fig. 5. The selected point of the graph has been shown in the curser with a length of 0.03m and creating 51^0 of impedance angle. The angle has not been changed from the initial stage of manufacturing defect detection stage of 51^0 to 51^0 not showing a vast impedance angle difference as shown in Table 3. A higher barrier to the flow of eddy current loops has occurred rather than manufacturing defects, so the impedance voltage has been changed from 0.23V to 0.33V. With the increment of the loads from 0.6Nm to 6.0Nm, it can be understood that the CF sample has been damaged gradually. Then the carbon fiber fabric with resin and hardener mixture has been detached or delamination had been grown producing a huge failure with a large conductivity barrier.

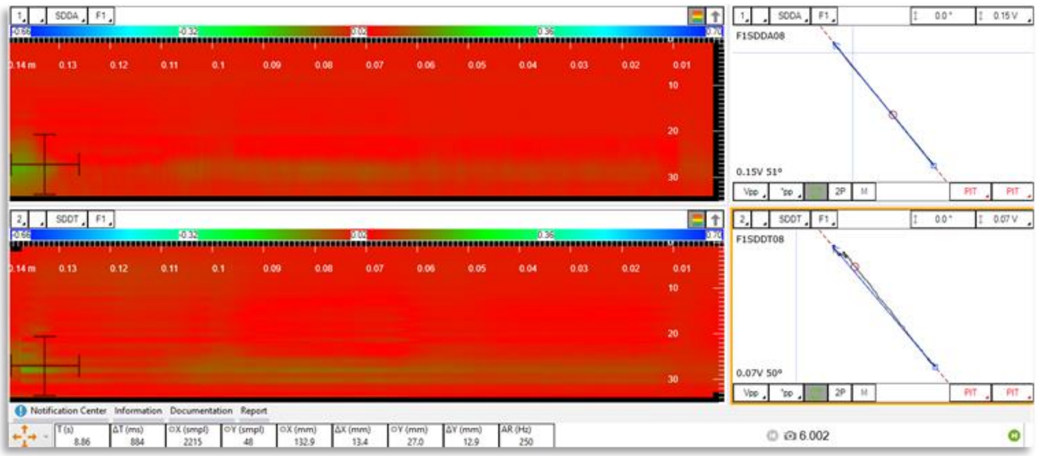


Fig. 6. Hammer impact damage results

The Fig. 6. indicates the hammer impact damage, visualizing and propagating on C-Scan plane. The impedance angle here is 51^0 as same as previous. In here the impedance voltage has been grown to 0.15V. With the high impact on the CF sample, the crack on 6.0Nm force has been grown with the hammer impact. On the transverse impedance plane, that change can be seen clearly. The delamination on 6.0Nm impact has been developed also. The CF strips were terribly damaged with the hammer impact. Discharge failure (failure of laminate) has been propagated gradually too.

Then with the increment of the defect can be identified.

- The impedance visualization is irregular.
- C-scan visualization is also difficult to clarify.
- The irregularity of the crack propagation can be seen clearly.
- Impedance angles with voltages have been shown to be an irregular variation.
- With the irregularity of the crack, the barrier to the penetration of eddy current is also high.

4 CONCLUSIONS

With the obtained Eddy current inspection data, invisible manufacturing damages such as matrix cracking, de-bonding, discharge (failure of laminate), Resin free areas, catastrophic failure, could be seen [12].
Those might be occurred.

- With the incorrect resin and hardener mixer
- The variation in temperature
- The quality of the hardener and the resin types
- Manufacturing faults in carbon fiber fabric

- The coating speed and sudden desiccation in resin and hardener mixer
- Delay in layer positioning after one layer is placed.

The above controllable and uncontrollable factors are affected by the manufacturing defects. With the correct manipulation of them, manufacturing defects could be minimized or eliminated.

During the manufacturing stage of the carbon fiber woven fabrics - CFRPs, the strips might have some damage. Even after the sample making process, the strips might create spaces allowing resin and hardener mixture to the longitudinal strip spaces. Those kinds of spaces would occur because of the looseness of fiber strip braids or the errors in the over under woven of the fabric.

In here CFRP plain weave was used. Rather than that, other woven patterns such as twill and unidirectional can be used for sample making process. Various kinds of CF woven fabrics have been manufactured to sustain good manufacturing and structural properties.

This sample was made in Badulla District, Sri Lanka where the weather condition was cold with compared to other provinces in Sri Lanka. Then climate changes might have affected the dry and cure process of the sample also.

To compact the layers, a special method was not used here. Manually layer by layer were stuck using a brush and a wooden roller. Then throughout the CF sample the compact pressure is not remain same. An equal pressure cannot be maintained manually because of the status of the resin-hardener mixture. With exposure to the environment, the resin-hardener mixture leads to dryness. To control that, the layer making process must be done rapidly. Otherwise resin free areas, void bubbles might occur.

With the impact damage, visible and/or invisible damage on the layer could be seen through Magnifi screen. visible damage can be detected, and initial steps can be taken to reduce or eliminate those effects, without going for a collapse or sudden destruct with the CFRP applications. But any invisible crack may lead to the CF application for a sudden failure making a destruction. Then, the accuracy of the damage detection technique is highly essential for different kinds of industrial applications, to retain a good name and save lives of human beings too. In 6.0Nm and hammer impact defects, the C-Scan results indicate that the catastrophic failure has been done. With such a visible change in C-Scan plane and impedance angle the destruction on CF sample can be well defined.

ECT simulation of CFRP composite plate with simulated damages such as fiber misorientation, waviness and wrinkling, indicated the changes in coil impedance were sufficient to enable the detection of such manufacturing flaws; these impedance changes were observed as the coil was moved between pristine and flawed areas.

Experimental ECT scans confirmed the capability of detecting manufacturing flaws in specially built specimens. In this experiment, it was investigated manmade CFRP specimen with a manmade crack. The results demonstrated the capability of Eddyfi system with Flexible Array probes to detect manufacturing flaws in CFRP composites.

Under the electromagnetic induction theory, the eddy current loops are gone deep of the damage even through small invisible defects. Those can be observed through Eddy current (Eddyfi) machine. Although the Eddy current NDT machine is at high cost, the accuracy of it is in a maximum level, as same as CF material prices are very high but it is a lite weight even after manufacture of the applications and also it is strong compared to other materials such as steel and iron

As Eddy current NDT can be used for only conductive materials such as CF and glass fiber applications to detect surface and near surface defects and they are limited with the inability of detecting defects on non-conductive material.

Based on theoretical and experimental results presented, it appears that ECT is a better methodology for detecting manufacturing defects in CFRP composites. In some cases, ECT was able to detect flaws rather than other NDT techniques such as ultrasonics and magnetic particle inspection were unable to detect them.

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