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Cost-effective structural health monitoring of FRPC parts for automotive applications

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Abstract—In the automobile industry, structural health monitoring of fiber reinforced polymer composite parts is a widespread need for maintenance before breakdown of the functional elements or a complete vehicle. High performance sensors are generally used in many of the structural health monitoring operations. Within this study, a carbon fiber sewing thread has been used as a low cost laminate failure sensing element. The experimentation plan was set up according to the electrical conductance and flexibility of carbon fiber threads, advantages of preforming operations, and sewing mechanisms. The influence of the single thread damages by changing the electrical resistance and monitoring the impact location by using carbon thread sensors has been performed. Innovative utilization of relatively cost-effective carbon threads for monitoring the delamination of metallic inserts from the basic composite laminate structure is a highlighting feature of this study.

Keywords: Composite material; metallic inserts; structural health monitoring; stitching technology.

1. INTRODUCTION

Monitoring of aging fiber reinforced polymer composite (FRPC) structures is an issue of great concern in the engineering area. Multi-site fatigue damages, hidden cracks in hard to reach regions, and corrosions are among the major flaws of apprehension. The use of condition-based maintenance coupled with continuous online structural integrity monitoring could significantly reduce the costs of inspection programs [1]. ‘Exclusion-for-cause’ instead of ‘exclusion-as-planned’ could reduce the costs while maintaining a safe operation life. The replacement of the present manual inspection with automatic structural health monitoring (SHM) would substantially reduce the associated lifecycle costs. Hence there is a need for reliable structural

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health monitoring systems that can process the data automatically, assess structural conditions, and signal the need for corrective action. Thus, the development of a real-time, in-service structural health monitoring, and damage detection technique has recently attracted a large number of academic and industrial researchers. The goal of this research is to allow systems and structures to monitor their own integrity while in operation and throughout their life in order to prevent catastrophic failures and to reduce the costs by minimizing explicit maintenance and inspection tasks.

The most popular approach to structural health monitoring is to use modal parameters, such as natural frequencies, damping ratios, and mode shapes to determine the existence of structure damage. Adams *et al.* [2] found that a state of damage could be detected by a reduction in stiffness and an increase in damping. A method to locate damages from measurements of natural frequencies was also demonstrated [3]. Other modal properties, such as sensitivity [4], eigenvector and eigenvalue matrix [5], curvature mode shapes [6], modal assurance criterion [7], and energy transfer ratio [8], have been examined for damage detection. Aktan *et al.* [9] presented an extensive work on civil infrastructures monitoring. Use of piezoelectric material for the structural health monitoring is well established [10]. Even the piezoelectric patches can be used not only for monitoring of the resin flow during the resin transfer molding (RTM) process but also for lifetime monitoring of FRPC parts [11]. Piezoelectric sensors have a number of advantages but disadvantages too, which makes their usability in composite SHM difficult. The disadvantages are: brittle due to crystalline structure, cannot withstand high shear and tension, material does age, uses active control (can lead to instability), and can become depolarized (high voltages, high temperatures, large stresses). Apart from this, PZT is a non-reinforcing material; thus, use of matrix compatible CF thread can be introduced for SHM.

In recent years, studies on neural networking [12], wireless active sensing [13], and wireless monitoring [14] are growing. In composite engineering, wireless monitoring is a very effective method for implementation but the costs involved in the implementation of health monitoring technology are too high. Thus, development of a cost-effective method is obligatory. Within this study, carbon fiber threads (CF sewing thread patented by IVW GmbH [15], IVW-CF thread) have been used as a health monitoring element.

1.1. Carbon fiber patches

In the past, some of the researches have concentrated on the carbon fiber itself as a monitoring element but mostly they preferred to use carbon UD-fiber patches.

Smart patches made up of uni-directional (UD) carbon fiber sheets can be used for damage detection. The change in the electrical resistance of carbon fibers as a response of impact will be detected by this method. Figure 1 shows the arrangement of carbon fibers and corresponding electrical conductive elements with varied electrical resistance. The theoretical background has been explained by

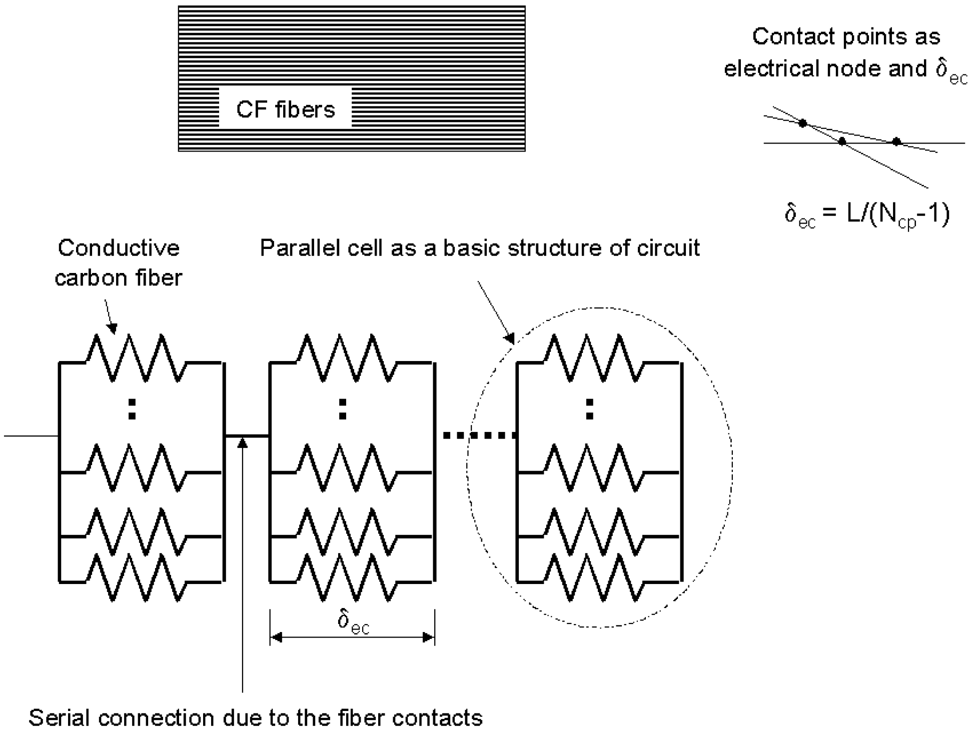

Figure 1. Schematics of CF patch and sensing behavior of fiber.

Takeda *et al.* [16, 17]. The deformation of conductive carbon fibers can be written as:

$$\frac{\Delta R_{\text{cf}}}{R_{\text{cf}}} = \alpha \frac{\sigma}{E}, \tag{1}$$

where R_{cf} is the resistance of carbon fiber; ΔR_{cf} is the change in resistance of carbon fiber; α is a constant; σ is the stress; and E is Young's modulus.

Fiber breakage or deformation due to elongation after the impact will be considered as a loss of conducting path. The amount of fiber volume content affects the effective electrical length, in other words δ_{ec} varies for different fiber volume fractions:

$$\delta_{\text{ec}} = L/(N_{\text{cp}} - 1), \tag{2}$$

where δ_{ec} is the electrical ineffective length, L is the fiber length, and N_{cp} is the number of contrat points (Fig. 1).

The aim of this study is to develop structural health monitoring based on the electrical properties of carbon fibers. Manufacturing of separate carbon patches requires an extra process, and an exact positioning of the patches is necessary. Thus, within this study, benefits of carbon fiber sewing threads (IVW-CF) have been utilized to validate their usability as a health monitoring element. The reason behind the selection of IVW-CF threads for the experimentation was based on laminate performance and consistency in material utilization (only reinforcing fibers in the structure of the laminate). IVW-CF thread is very thin and flexible; therefore, it is suitable for stitching composite panels. The special construction of threads enables us to stitch metallic inserts by forming several loops without damaging individual carbon filaments. Use of foreign materials as a sensor system that will be a part of the laminate may affect adversely the laminate properties. The reason behind this is that sensors integrated into the laminate may disturb the reinforcing fiber orientation. Furthermore, the integrated IVW-CF thread sensor shows real intensity of damage as these threads represent sections of the actual load carrying laminate. Apart from this, distribution of carbon threads over the complete area of the component is easily executable.

Selection of the experimental sensor is based on the goals to be achieved and allowed time-frame for successful development of a sensor system, which follows the criteria of:

- Cost of the sensor system and accessories: For the initial trials the costliest sensor system may not be worthwhile, and furthermore for extensive applications of the sensors, the basic system should be of marginal cost.
- User friendliness: The complete system needs to be easy in monitoring which helps to detect damages quickly.
- Observation area (effective sensitive area): Observation area depends on the number of sensors involved in the part. Furthermore, IVW-CF threads are relatively cheap, so more can be put into the structure. Thus, damage detection will be easier in this case.
- Robustness: The used sensors should not susceptible to damage during the integration process. Unlike optical fibers and piezoelectric sensors, CF patches are more robust and easy to handle during the integration process (for instance during performing, sewing, and resin transfer molding).
- Sensitivity: Sensitivity of highly sophisticated sensors is not a big question but when it comes to the robust, user friendly IVW-CF thread sensors; its sensitivity is not like piezoelectric patches but enough to distinguish generated signals.

The test plan is based on the carbon fiber reinforced polymer uni-directional-grid, which will be placed on the glass fiber preforms and the change of the electrical resistance of carbon fibers will be measured. SEN-T test, metallic insert failure test, and impact test of glass fiber reinforced laminates were performed to prove utility of electrical resistance of carbon thread, to analyze debonding of individual stitch at insert and its influence on the change in resistance, and rupture of carbon thread to locate approximate failure location respectively. All the three tests can show different aspects of carbon thread utility for structural health monitoring.

1.2. Selection of material and specimen manufacturing

Carbon fiber thread (IVW-CF) was used as an intelligent monitoring material. Plain woven (200 g/m^2) and bi-axial noncrimp fabric (NCF 250 g/m^2) made of glass fiber was used as textile reinforcement. Composites were manufactured by using an epoxy matrix system (RIM 935 + RIMH 937 from MGS Kunstharzprodukte GmbH) and vacuum assisted resin transfer molding technique.

1.2.1. Specimen development for tensile tests. For tensile tests (single edge notched tensile, SEN-T), glass fiber woven fabric has been used as base material. Preforms were stitched in such way that the carbon fiber thread position was in a straight line without deviation. Modified lock stitches provided the advantage of being able to position the roving at the bottom of the preform. Here, a polyester multifilament thread was used as a needle thread and a IVW-CF thread was used as a bobbin thread (Fig. 2). Stitching parameters used for preform manufacturing are stated in Table 1.

The manufactured panels were then injected by means of a liquid matrix based on an epoxy system. The standard vacuum assisted resin infusion (VARI) method was used for manufacturing the laminates. Lay-up building on the heating plate for the VARI process involves the following steps: (a) coating of release agent;

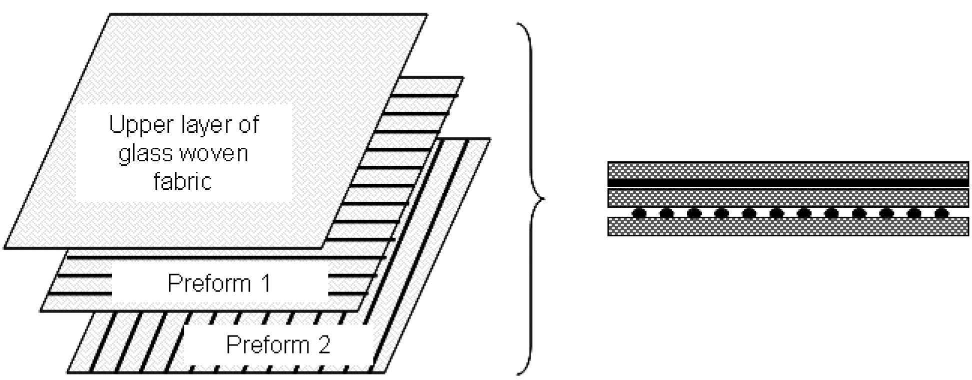

Figure 2. Schematic of lay-up for CF grid formation.

Table 1.
Parameters of preform manufacturing

Fabric used	Glass fiber woven fabric/noncrimp fabric
Stitching machine used	Pfaff 3574
Stitch type	Modified lock stitch (bobbin thread at the bottom)
Stitching speed	1000 1/min
Needle thread force	320 cN
Bobbin thread force	140 cN
Stitch length	3 mm
Smart element	IVW-CF thread (used as bobbin thread)

Table 2.
VARI process parameters

Release agent	Freekote
Preform material evacuation	10^{-2} mbar, 1 h
Matrix used	VE 4908 A + B
Degassing of liquid matrix	10^{-1} mbar, 10 min
Vacuum during injection	1–10 mbar
Injection time	15 min
Curing	80°C, 6 h

(b) sewn preform panel (IVW-CF threads facing top); (c) glass fiber woven fabric; (d) perforated foil; (e) distribution media (glass fiber mat); (f) vacuum foil. The glass fiber woven fabric (position c) helps to avoid direct contact of IVW-CF thread to the test instrument in the later stage. Tacky tape was used as a vacuum foil sealing medium. Table 2 shows the typical parameters set for the VARI process. Manufactured panels were then cut to the exact size for SEN-T testing.

1.2.2. Manufacturing of CF thread grids. Manufacturing of CF grid by using sewing threads without contacting 90° CF rows with the 0° rows was performed for impact test specimens. Here the base glass fabric for 90° rows works as an insulator between 0° and 90° rows (Fig. 2). Two sub-preforms per panel were manufactured. Each preform consists of CF thread rows. All tests were carried out with the same parameters as stated in Table 1. The manufactured dry preform panels were then placed in the proper position and then injected to obtain the required grid laminate. The construction of the lamination lay-up was designed by considering the influence of the laminate surface (CF thread distribution) and the thickness, which determined the sensitivity of the plate. The parameters for VARI process were in all tests the same as stated in Table 2.

1.2.3. Manufacturing of preforms with inserts. Another use of CF patches/threads considered was the monitoring of the delamination of metallic inserts. For these tests, inserts and glass fiber NCF were stitched together by using polyester multifilament twisted threads. Here, the NCF was used as a preforming material. The IVW-CF thread was used to form seams at the critical positions, which are supposed to be the delamination initiation zones (Fig. 3). These seams were connected with a conducting wire, which is not a part of the whole laminate.

Figure 4 shows a preform sewn with the polyester thread and then with the IVW-CF thread including electrical connection. Six of such preforms were injected simultaneously by using a special designed tool. The tool helps to inject only the base of the insert and the reinforcing glass fabric.

Preforms with inserts for delamination sensing were manufactured according to the measurement reliability. All the sewn preforms were then injected and tested for the reliability and exactness of measurement.

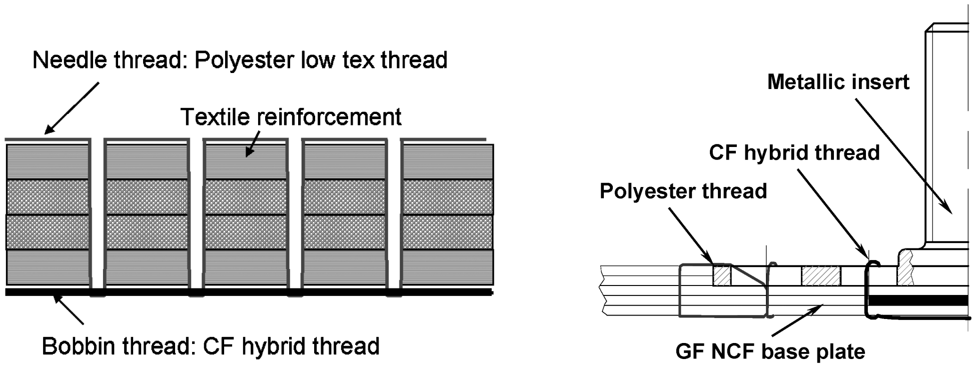

Figure 3. Modified lockstitch for monolithic laminate and insert monitoring.

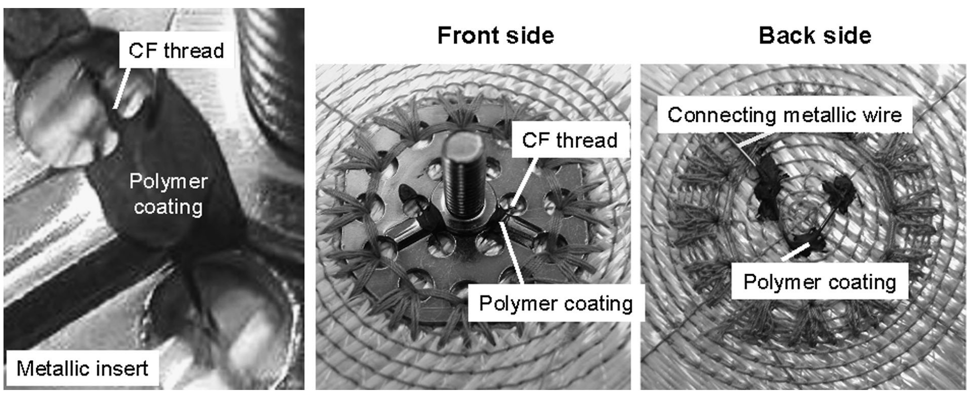

Figure 4. Insert preform with sewn IVW-CF thread.

2. EXPERIMENTATION AND RESULTS

2.1. SEN-T test

The schematic of the specimen and the experimental setup used in this study are shown in Fig. 5. A Zwick 1474 tensile testing machine was used for testing. The machine works on the principle of constant rate of traverse. The specimen dimensions are stated in Table 3. A specimen is mounted on the machine and CF threads are internally connected by using electrical wires. Both ends of the specimen were then connected to the signal converter which is connected to the plotter. As the test progresses, due to applied force, the individual CF thread starts breaking until the complete specimen fails. A failed specimen is also shown in Fig. 5.

During the failure mechanism, due to the gradual breakage of individual CF threads, the voltage value increases, which can be later calculated in terms of change in electrical resistance. As shown in Fig. 6 the force *vs.* displacement diagram correlated with the voltage *vs.* time diagram.

The voltage *vs.* time diagram is helpful to analyze phenomena of through-the-thickness changes in the electrical resistance. As shown in the same figure, there is

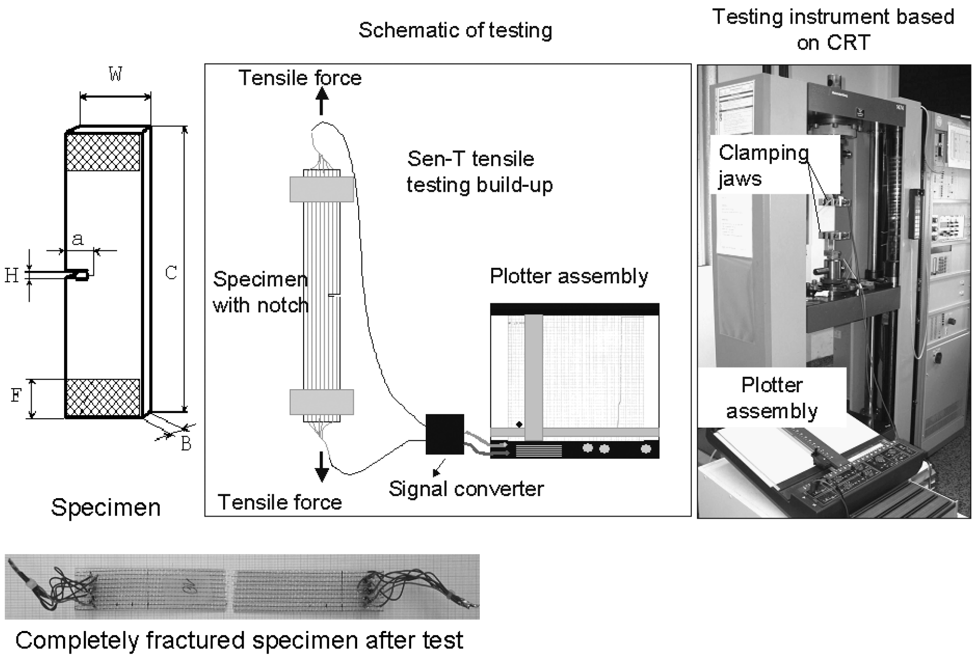

Figure 5. Specimen dimensions for SEN-T test and testing instrument: schematic diagram, machine set-up, and tested specimen.

Table 3.
Specimen specifications for SEN-T test

Width (W)	30 mm
Length (C)	110 mm
Thickness (B)	1 mm
Notch length (a)	10 + 1 mm
Notch width (H)	1 mm
Clamping length (F)	15 mm

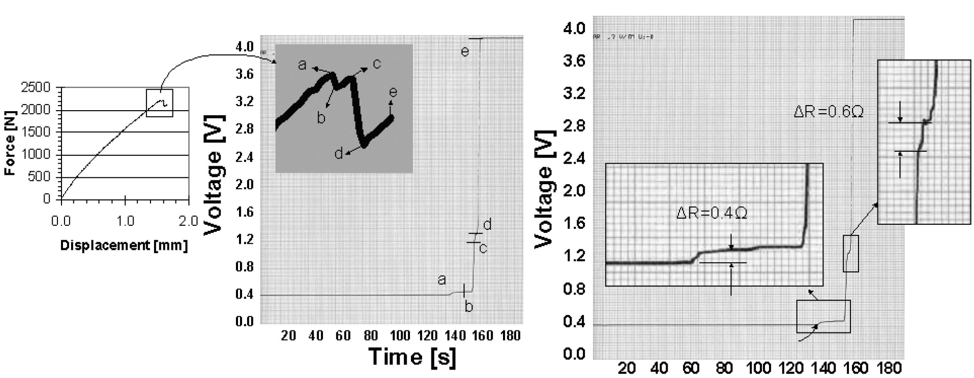

Figure 6. Force–displacement diagram, failure and corresponding voltage peaks and plot diagram of change in voltage on time scale during the test.

very low electrical resistance at the initial stage and as the CF threads start breaking the electrical resistance starts increasing and at the end it reaches to infinity. The gradual increase in the electrical resistance from 14 Ω to ∞ and the corresponding peaks on the plot diagram are shown in Fig. 6 (equation for calculating R from value of V is $V = IR$).

Due to the working principle of the testing instrument (constant rate of traverse) the time required for initial breakage is too high compared to the final thread breakage. Thus, on the time scale the occurrence of the peak is very quick at the end of the test, but the change in electrical resistance is still visible. The changes in resistance values calculated from the plot diagram are very small but not invisible. Magnification of signals will be helpful while implementing this technology in the final product assembly.

This test helps to monitor changes in resistance of carbon threads before and after fracture and thus helps to validate usability of threads as a sensor in the components subjected to tensile strength or even extreme bending where tensile force is involved. Broken or elongated carbon fibers show reduced resistance and help to conclude intensity of damage corresponding to electrical resistance.

2.2. Impact test

The test instrument used for impact testing was from company Ceast, with code: 6789/000. The grid panels were tested with different impact speeds and its influence was monitored on the basis of impact intensity and damage caused (visual analysis). The impact velocity has been changed on the basis of distance between specimen and impact tool. Table 4 shows experimentation data used for the impact testing. The force and energy data for different impact velocities during the test was monitored. According to the intensity of the impact, the damage of the FRPC laminates was monitored and tested for change in the resistance at the exact location of the impact. Figure 7 shows the laminate sections at the damaged locations with different impact energy. From these figures, the relative damage intensity can be judged but the actual through-the-thickness damage at the laminate section was monitored on the basis of change in electrical resistance of the CF thread.

Table 4.
Experimentation data for impact testing

Diameter of impact rod (mm)	20
Weight applied (kg)	8.357
Impact velocity (m/s)	1.0
	2.0
	2.5
	3.0
Working temperature	RT (24 ± 2°C)

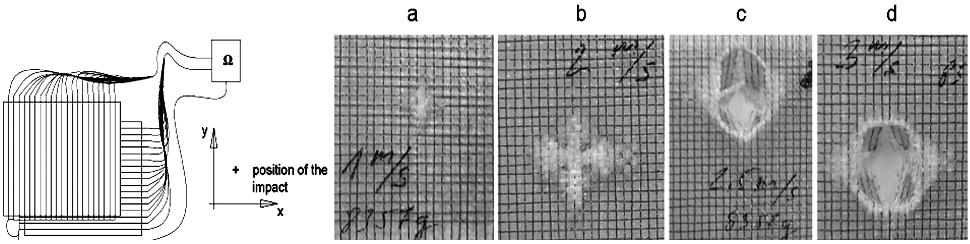

Figure 7. Results of impact test (damaged zones) with different speeds: (a) 1 m/s, (b) 2 m/s, (c) 2.5 m/s and, (d) 3 m/s.

The change in the resistance through the CF threads in both X and Y direction of the grid was monitored and transferred to the excel data sheet. The results were then graphically analyzed. The graphic representation helped to locate the exact position of the damage (corresponding to X and Y CF sensor). The user friendly diagram illustrates the damage location on the scale of the part geometry.

Figures 8 and 9 show the plots of the CF threads and the corresponding change in '1/resistance' as well as the location of the damaged zone.

As shown in the above figure, the Y coordinate shows two adjacent peaks on the zero axis at the 49th and 50th CF sensor position and on the X coordinate only a peak at position 54th CF sensor. After combining those results, the position of impact according to the X and Y coordinate can easily be plotted on the actual part scale.

Two impact tests were carried out to show the possibility to monitor CF laminates with CF fibers. In the first test, the CF thread was placed directly on the CF laminate. In the second test, a glass felt with the specific weight of 50 g/m^2 was placed between the CF laminate and the CF monitoring rovings.

The results of the test showed that it is not possible to use CF threads to monitor a CF laminate without isolation (Figs 10 and 11). In this case, only the resin is not adequate to insulate the thread from the carbon fiber laminate completely. The second test showed that, due to very low specific weight, this glass felt was insufficient to separate the CF thread and the CF laminate. If no insulation is used between the CF laminate and the CF thread, the electricity flows through the plate and therefore, it is not reliable to monitor the impact. However, if insulation is used, the impact on the CF laminate can be easily monitored.

The impact test was used to monitor influence of impact damage on overall sensing capacity of carbon thread. Here, damaged zones can be denoted as the only section where the CF thread is damaged. Delamination around the fractured surface is not appropriately detectable, thus, this technique is not well suited for minimal impact with little damage.

2.3. Insert pull-out test

IVW-CF thread integrated (sewn) metallic fasteners were tested to monitor delaminations of metallic parts from the glass fiber reinforced polymer composite. Mon-

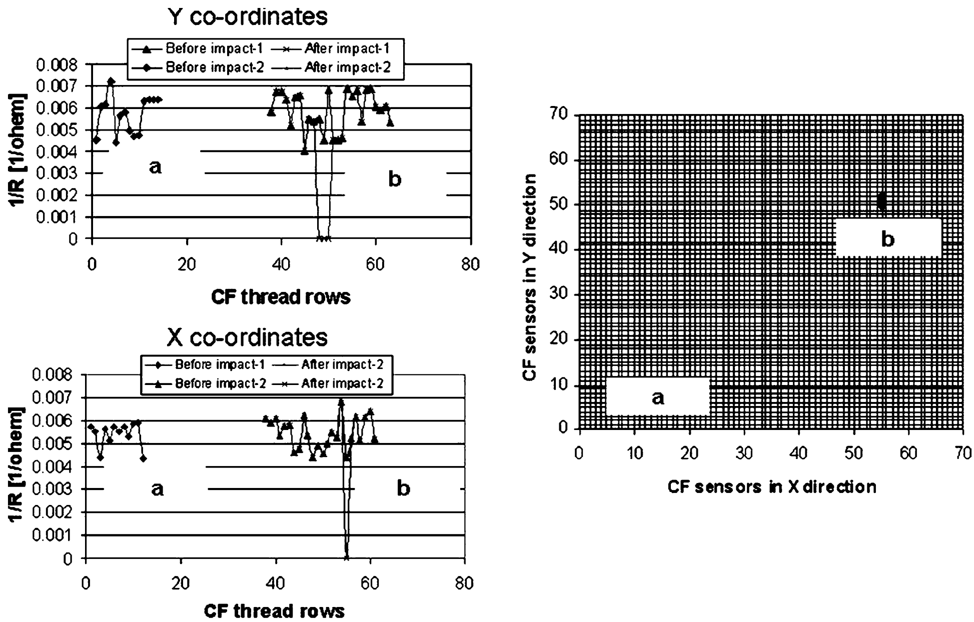

Figure 8. Positioning of impact location according to change in resistance values (low impact).

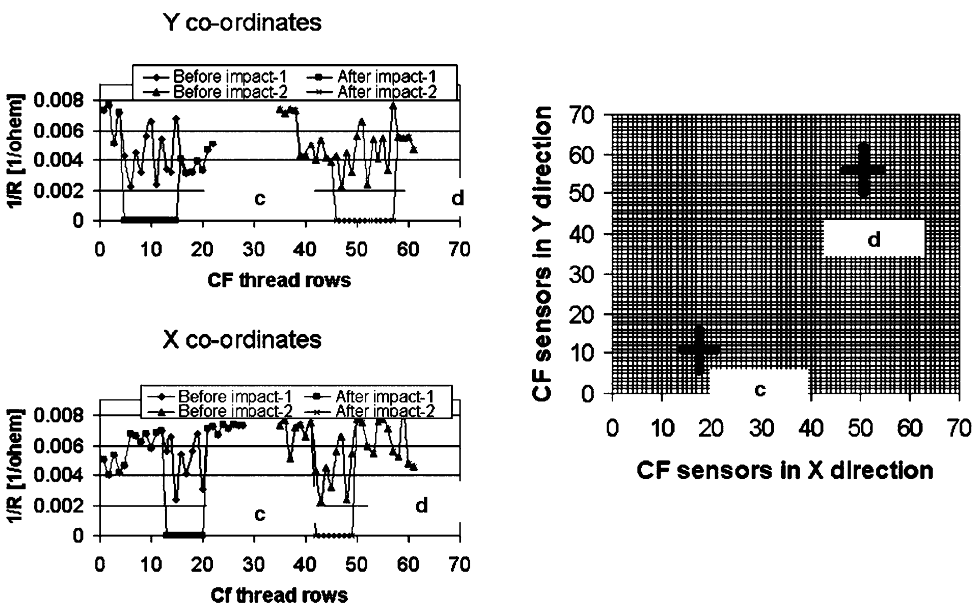

Figure 9. Positioning of impact location according to change in resistance values (high impact).

itoring the first delamination and the corresponding change in resistance shown by the CF thread was the basic concept behind this experiment. The testing instrument (b) and the close-up view of the test rig (c) is shown in Fig. 12. A Zwick 1474

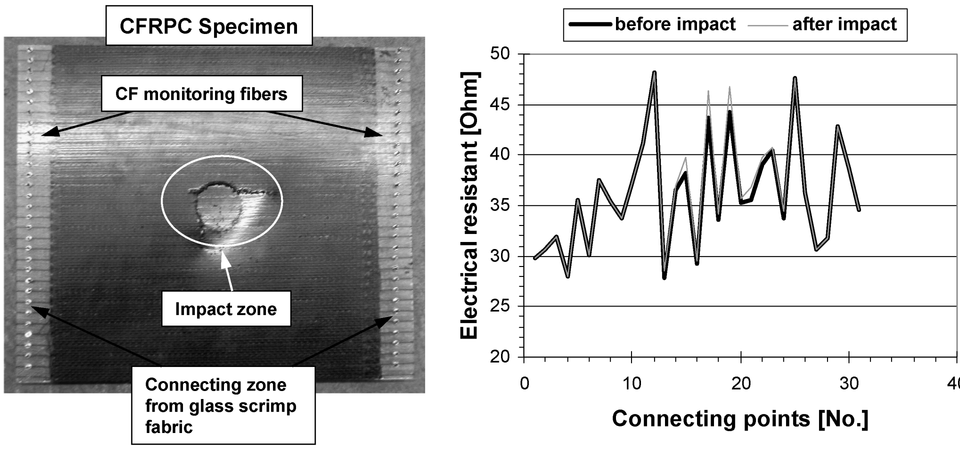

Figure 10. Results of impact test on the CF plate with CF monitoring fibers.

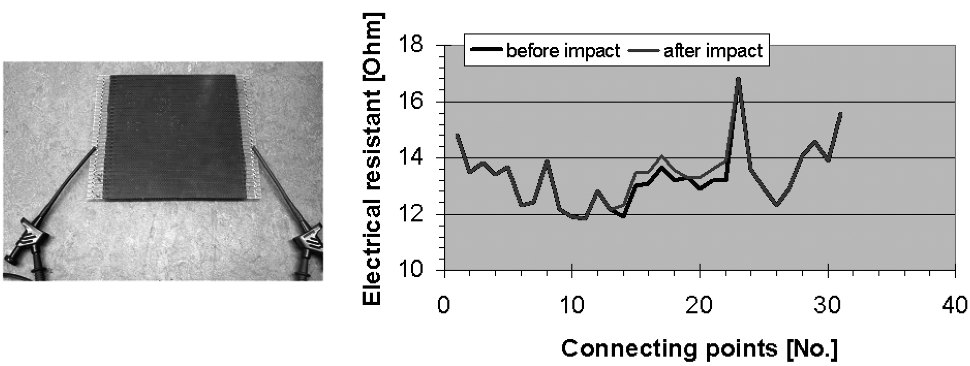

Figure 11. Change in resistance values before and after impact (specimen with glass mat).

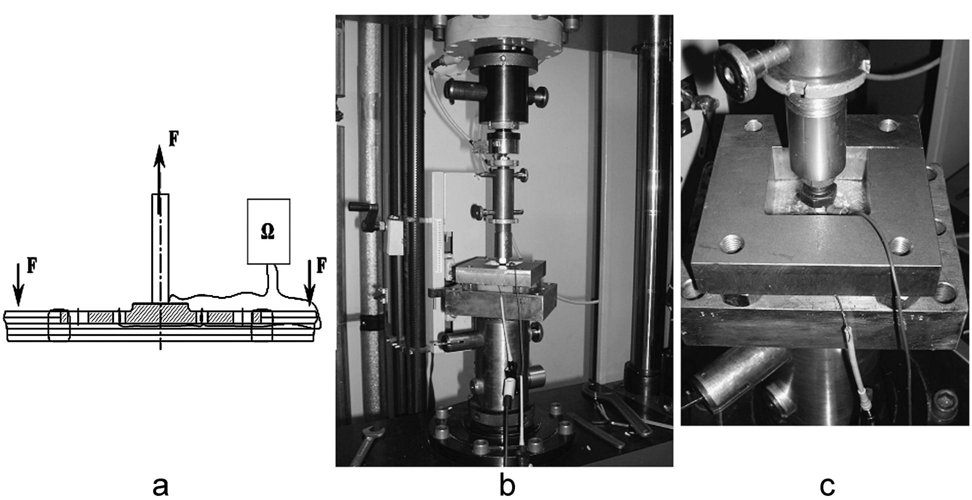

Figure 12. Insert testing set up: (a) schematics; (b) complete instrument; (c) close-up of test zone.

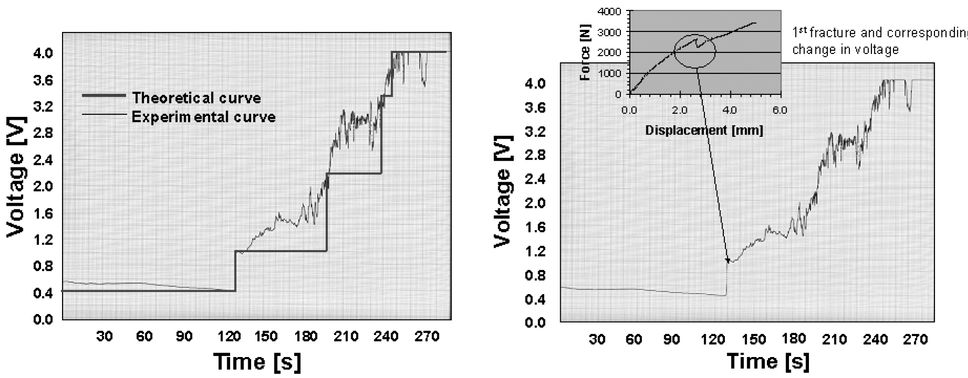

Figure 13. Influence of CF thread breakage on change in voltage and comparison of force displacement diagram and change in voltage.

tensile testing machine was used for the testing. Figure 3 shows stitched inserts and the position of the CF threads at the critical delaminating zone under the threaded bolt and connecting metallic wires. The CF seams are connected to the metallic wire and the section of metallic fastener. This wire is than connected to the signal converting unit and then to the plotter.

As the experiment progresses, the tensile force applied on the metallic insert pulls the CF thread (stitch) in the vertical direction [18]. The corresponding change in voltage shows no change till the first delamination and CF thread break. The critical area is under the threaded bolt of the insert.

Figure 13 shows the plot of change in voltage *vs.* time. After the first CF seam breakage, a peak of change in voltage forms and follows the same trend after the breakage of the subsequent seams. Theoretically, the plot should show a sudden deflection on the voltage scale after the damage of the carbon fiber sensor. But practically the phenomenon of CF thread breakage and possible contact between broken filaments shows the progressive deflection of the curve. Figure 13 shows that the first delamination of the insert where the CF thread breaks and the first voltage rise occurs takes place at the same time.

Incorporation of a very little amount of CF thread at the exact damage prone zone will help to validate the thread usability for integration of metallic inserts in the FRPC laminates. Strain caused in the CF thread during initial load can also be detected in terms of minute change in resistivity. However, major damage in insert bonding with the main laminate can be easily detected.

3. CONCLUSIONS

The use of IVW-CF sewing thread as a sensor system for life cycle monitoring and life expectancy of fiber reinforced composite seams is advantageous. The results of different tests based on various forms of CF-thread placement shows the effectiveness of the system. IVW-CF thread works as an integrated part of the laminate; thus, the influence of the CF thread damage on the change in resistance helps to monitor real fracture impact of the FRPC. The robust nature of the sensors and cost-effectiveness of incorporation processes (process of sewing is relatively cost effective for sensor mounting and the costs of IVW-CF thread compared to modern sensing systems is very low) increases the possibility of using these sensors in automotive parts. The current monitoring system with CF thread can be made more accurate by improved connectivity between sensor and monitoring instrument. The measurement system can be made more user-friendly and accurate. Implementation of CF sensors only at the critical zones reduces the efforts of monitoring the complete part area or volume and still provides the required damage information.

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