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MULTIFUNCTIONAL WEFT-KNITTED FLEXIBLE COMPOSITE STRUCTURES(ORAL PRESENTATION)

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ABSTRACT

Multifunctional composite structures offer unique features such as the ability to sense and respond to external stimuli that can be force, pressure or temperature. Knitted preforms are popular due their excellent properties like flexibility and impact resistance. So far, most of the research is focused on mechanical properties of rigid knitted composites structures. In this research, a preform for a composite is produced having a knitted functional sensing layer constructed using stainless steel yarn. The flexible knitted composite is developed by treating the knitted preform with a flexible resin via vacuum infusion process. The characteristics of the functional layer are investigated at the preform stage by carrying out tensile and cyclic tests. The results from these experiments show that the design of the knitted sensing preform has a substantial effect on the sensor sensitivity under different extension regions.

*Key Words***:** *Multifunctional composite structure, functional/sensing layer, Flexible knitted composites, sensor sensitivity*.

1. INTRODUCTION

Textile reinforced composite structures have emerged as a popular candidate due to their excellent properties as being light weight along with high strength and stiffness [1-4]. However, sometimes during use these composite structures are susceptible to matrix cracking which can lead to delamination. The delamination would result in the failure of the structure and it can happen without sufficient notice. Such failure can be avoided by continuous monitoring while they are in use, which is possible through the integration of sensors within the composite structure.

This aspiration has led scientists to develop functional structures with enhanced features. The functional/intelligent structures are termed as multi-functional structures because they perform multi-tasks such as sensing apart from load bearing [5, 6]. It enhances the structural performance by enabling continuous monitoring of the structure while in its operational phase [7].

The integrated sensing feature of the preform structure can be created for monitoring conditions such as force, vibrations, pressure, and temperature. The working principal of the sensor can be based on different phenomenon such as resistive, piezo-electric or optical sensing [4, 8-11]. Nevertheless, the integration of electronics within the reinforced composite could present challenges in terms of structural integrity. This is mainly due to conditions such as electrical components can act as a foreign entity which could significantly affect the mechanical properties of the reinforced structure [12-14]. This can be avoided by selecting appropriate sensor size, shape and form. In this environment, an attractive solution can be created by using electro-conductive yarn based sensors which can be integrated in to the preform structure during its manufacturing stage. The conductive yarn becomes a part of the preform structure without affecting the preform production process [15-17]. Furthermore, it can be cost effective from production point of view.

Currently the researchers working in this area are investigating the possibilities of developing smart composite structures by integrating sensors at various scales i-e from macro to nano On macro scale, optical fibres are embedded within the laminated composites to sense strain experienced by them during curing and loading conditions [18-20]. The optical fibre works on the principal of variation of known spectrum of light passing through it. These sensors are highly sensitive and respond to changes such as temperature and strain very accurately. They have been used successfully within reinforced composite structures [21, 22]. However, in these instances, the setup for data acquisition is expensive and the size of optical fibre can affect the mechanical properties of composites [23-25].

Similarly, piezoelectric based sensor is another example where composite structural monitoring is carried out on a macro scale. There is evidence that both of these methods have been extensively used for non-destructive evaluation of composite structures. Piezoelectric sensors produce output voltage under mechanical force and mechanical deformation under applied voltage [14]. This piezoelectric effect facilitates the sensor to be used in both active and passive sensing mode [26]. For health monitoring of structural materials, Impedance-based and lamb wave propagation method are classed as an active sensing mode [27]. While, getting sensor response under external stimuli such as tension, compression and impact testing is considered as passive sensing. There is evidence that both of methods have been extensively used for non-destructive evaluation of composite structures [10, 28-30].

Likewise, resistive sensors are also used for health monitoring purpose from macro to nano scale. The sensors respond to external mechanical force as a function of resistance change [31] . In this area, one of the interesting candidates is carbon nanotubes which are a highly sensitive resistive sensor type due to its inherent piezo-resistive effect [32-35]. Within fibre reinforced composite structures, this property can be utilized to create a nanoscale strain sensor by mixing within matrix of composite material [25, 36]. Any change in resistance under loading conditions is attributed to the scale of damage initiating from nano scale and progressing to micro scale. The benefit of mixing carbon nanotubes with the matrix is two-folds; 1) nonintrusive 2) improved mechanical properties. The nanotubes so integrated to the composite structures do not act as a foreign body and studies have found that their presence improved the mechanical properties [37]. The concept of creating conductive matrix is also investigated by using other fillers such as graphene, carbon black, carbon nanoparticle as well as metallic nanoparticles [38-41]. Several other approaches are also used as resistive sensors which include electro-conductive yarn, coated and thin film based sensors [16, 42-44].

Contrary to conductive matrix approach, some researchers have focused on reinforcement for monitoring purpose. In this respect, carbon fibre has been widely investigated on the basis of its electro-conductive nature. This property was employed to study damage initiation and progression experienced by carbon fibre reinforced structures [45, 46]**.** The change in the resistivity pattern of reinforcement is attributed to the fibre breakage under progressive loading conditions [47-49]**.**

A very important aspect of the smart composites is degradation of mechanical properties due to the sensor integration. Hence, various researchers have explored effect of sensor integration on the mechanical properties of composite structures [29, 50, 51]. They concluded that presence of sensor should have negligible effect on the structural integrity as it was found to affect mechanical properties significantly [13, 14, 52]. Therefore, with the fast development in nanotechnology, the concept of using nanoscale sensor is gaining more attraction than macro scale sensors.

The incorporation of a sensor within reinforced composite structure is done during two key stages: 1) preform manufacturing 2) Vacuum bagging [17]. Mostly, it is performed by embedding it within preform layers at the vacuum bagging stage [23, 35, 53]. The yarn based senor offer an attractive feature of being incorporated at the preform manufacturing phase. This integration at preform manufacturing stage is feasible from production point of view. Hence, this approach can yield a multifunctional preform at the manufacturing phase without affecting the overall process of preforming. Furthermore, the location of the sensor integration can also be customized, e-g insertion of sensor in warp or weft direction during weaving stage [16]. Hence, a customized smart preform can be produced by integration of either single electro-conductive yarn or a network in a predefined direction.

The preform can be carefully tailored according to the geometrical design by employing textile technological processes. Generally, Woven preforms exhibit high mechanical strength but knitted preforms offer additional advantages such as drapability, conformability and high impact resistance [54, 55]. The type of resin has a profound effect on the properties of the composite structures and its selection is influenced by application area. The flexibility of the structure is limited by using thermoset and thermoplastic resins. So, in order to utilize the flexibility of composite structure the resin should exhibit higher flexibility. By selecting such type of resin, the true essence of knitted preform can be utilized [56].

It is obvious from literature review that fibre reinforced knitted composite structures are investigated mainly in relation to their mechanical properties [57-59]. Although, knitted reinforcements are used for development of multifunctional composite structures. So far, most of the work is focused on development of multifunctional composite structures by using thermoset and thermoplastic resins [4, 15, 40]. This objective of this study is to develop multifunctional flexible composite structure by using a flexible resin. In this respect, the initial step is the development of sensing layer.

As previously mentioned, the most widely used approach for sensor integration is during vacuum bagging prior to resin infusion. This study has focused on utilizing weft knitting to integrate sensor during preform manufacturing phase. A sensing layer developed by this approach eliminates the need of embedding sensor yarn during vacuum bagging. The sensor used for this purpose is electro-conductive yarn. Several issues are addressed such as selection of appropriate knitted structure, sensing layer design and its characterisation.

The literature reveals that electro-conductive sensor yarn is characterised mostly in two stages; in yarn form and within the reinforced composite structure. However, in this study the focus of sensor characterisation is at the preform stage. The author believes that by using this approach it is possible to develop an appropriate sensor design which is able to undergo larger extensions. The sensor is characterised for its strain sensing and cyclic behaviour by using a half bridge circuit.

2. METHODOLOGY

The methodology involves development of functional preform during weft knitting process. The sensor is characterised for its strain sensing behaviour under loading conditions. The resistance change is correlated with the applied strain and behaviour in different regions is analysed. This section explains about introduction of the materials, theory behind the strain sensor, experimental design and electromechanical characterisation of knitted preform.

2.1 Introduction to the materials

The knitted smart sensing layer was developed by using glass yarn as reinforcement yarn while 100 % stainless steel was used as a sensor yarn. Glass yarn was obtained from the weaving department of the school of materials within the University of Manchester. Glass fibre was selected due to ease of processing during knitting process.

The conductive yarn was purchased from Bekaert Bekinox® and it was supplied under the trade name of VN 14/2x90/175S/316L. The stainless steel yarn is flexible yarn suitable for processing on the knitting machine. It was selected due to higher flexibility, conductivity and ability to withstand high temperature.

The conductive yarn is two ply yarns with 90 continuous filaments in each ply. One filament has a diameter of 14 μm as confirmed by SEM analysis as shown in the figure 1. According the supplier data sheet, the type of stainless steel yarn is 316L which is austenitic stainless steel.

The flexible resin was provided by the courtesy of PRF composite materials. It is new type of flexible resin which has very low viscosity and hence it can be easily applied during vacuum infusion process.

2.2 Theoretical aspect of Strain Sensor

A strain sensor responds to external force/pressure by changing its resistance. For a conductive material having length (L), cross-sectional area (A) and resistivity (ρ), the resistance (R) is expressed by following equation (1) [60].

$$R = \rho \frac{L}{A} \tag{1}$$

When a sensor is stretched or compressed its dimension changes which contribute to change in resistance. In case of tensile force, the sensor undergoes change in length from L to $L + \vartriangle l$, while the cross-sectional area changes to $A - \vartriangle a$. This would result in change of resistance from R to $R + \vartriangle r$. If $R_{original}$ is the initial resistance of sample and R_{change} is the resistance change experienced by the sample under force. Than the relative resistance change% experienced by the sample can be defined by the equation (4).

$$R_{change} = R + \vartriangle r \tag{2}$$

$$\Delta R = R_{change} - R_{original} \tag{3}$$

$$Relative\ resistance\ change\ \% = \frac{\Delta R}{R}\% = \frac{\boldsymbol{R}change - \boldsymbol{R}original}{\boldsymbol{R}original}\ \% \tag{4}$$

The gauge factor or the sensitivity of the sensor is defined as the ratio of the relative resistance change per unit strain experienced by the sample [61].

$$\boldsymbol{Gauge\ factor(GF)} = Relative\ resistance\ change \big/ Strain = \frac{\Delta R}{R} / \in \tag{5}$$

2.3 Experimental design

The stainless steel yarn was incorporated within the knitted preform during the weft knitting process. The sensing preform was produced on ten gauge weft knitting machine SHIMA SEIKI 122-S. Different sensor designs were produced and stainless steel yarn is incorporated within the structure by using two approaches ;laid in and knitted loops. The sensing preform was characterised for its strain sensing behaviour by electro-mechanical testing. Later on, a flexible composite structure was made via vacuum infusion process by treating preform with the flexible epoxy resin. However, this paper focuses on the development of sensing layer in relation to sensor design and its effect on electromechanical characterisation. The experimental design involves yarn characterisation, development of sensing preform and its characterisation at preform stage.

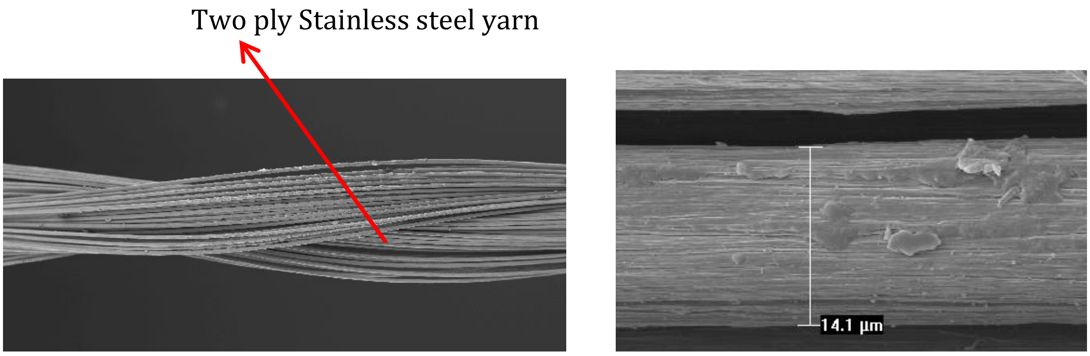
2.3.1 Yarn Characterisation

Glass yarn and Stainless steel yarn were characterised to evaluate certain properties such as linear density and tensile strength. Similarly twist per inch was evaluated for Stainless steel yarn. All of these tests were conducted according to the British standards and the results are mentioned in Table 1.

Table 1 Glass yarn and Stainless steel yarn characterisation

Types of Test	**Glass yarn**	**Stainless steel yarn** Twist type **“S”**
Linear density	276 ***(BS:947:1970)***	248 ***(BS:947:1970)*** (supplier information =250)
Average Breaking force	105.90N	44.442 N
Elongation at break %	2.52 % ***(BS ISO 3341:2000)***	1.43 % ***(BS: 2062:2009)***
Twist per inch	-------------	44 ***(BS:2061:2010)***

The Stainless steel yarn was also characterised by SEM analysis before and after the electromechanical tests for evaluation of any progressive damage. It is clear from figure 1 that the yarn consists of two ply with an average filament diameter of 14 µm.



(A) **(B)**

Figure 1 (A) Two ply continuous filament yarn at 100X magnification. (B) Stainless steel yarn at 4000X magnification; diameter confirmed by SEM analysis.

2.3.2 Development of sensing/functional layer

The development of sensing layer was achieved in several steps by using knitting process. They include selection of the base knitted structure and creating appropriate sensor designs.

2.3.2.1 Selection of knitted structure for sensing layer

The weft knitting process is utilized for development of sensing preform. In the initial phase, different types of knitted structures were produced on SHIMA SEIKI 122-S, 10 gauge electronic flatbed knitting machine. Four types of knitted structures were produced which include Full milano, 8-Lock, 8-Lock shift and interlock. These structures were analysed in relation to their physical appearance, number of wales and courses, stich density and mechanical properties.

Full milano structure was found to be best among all due to its stability and good mechanical properties. Therefore, it was chosen as the base structure for the development of sensing layer. The number wales and courses per cm were evaluated and they were found to be 5 and 8 respectively.

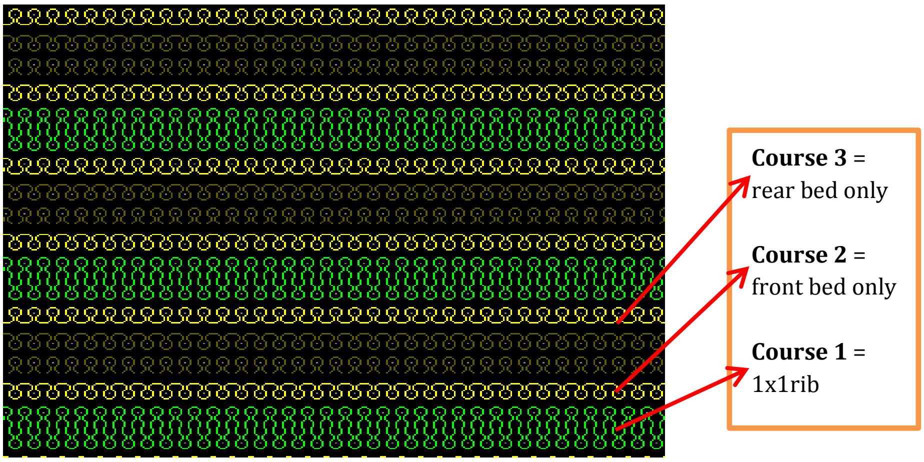


Figure 2 Full Milano Glass structure yarn path rotation.

2.3.2.2 Knitted preform sensor designs

The sensing/functional layers were produced on SHIMA SEIKI 122-S, 10 gauge machine by integrating stainless steel yarn in it. The electro-conductive yarn was laid in and knitted within the sensing layer. Three types of sensor designs were developed with the sample size of 190 x 50 mm.

1) Sensor design One (G-KSD 1,yarn laid in)
2) Sensor design two (G-KSD 2 ,yarn laid in)
3) Sensor design three (G-KSD 3,yarn Knitted)

Full milano glass knitted sensor design (G-KSD1) was created by applying laid in technique. The sensor yarn was laid in weft wise direction between two knitted courses of glass reinforcement. The ends of stainless steel yarn were knitted on each side to avoid slippage in the subsequent mechanical testing. The ends of SS yarn were left hanging outside the fabric for electrical connection to complete the circuit as shown in figure 3.

The sensor was laid in approximately in the middle of the sample which was around 25mm of the total width (50mm). The purpose behind this motive was to ensure that force is applied evenly on to the fabric. It was observed that the yarn was laid in slightly loosely between the courses. The slackness was removed by carefully stretching the yarn to straighten it. Here, the purpose was to make sure that sensor response is recorded in the initial regions of strain. The initial experiments failed to detect any changes in the resistance value in the initial regions of the strain. The reason was found to be the slackness of yarn and once it was resolved, the response of sensor was recorded successfully in the initial regions of strain.

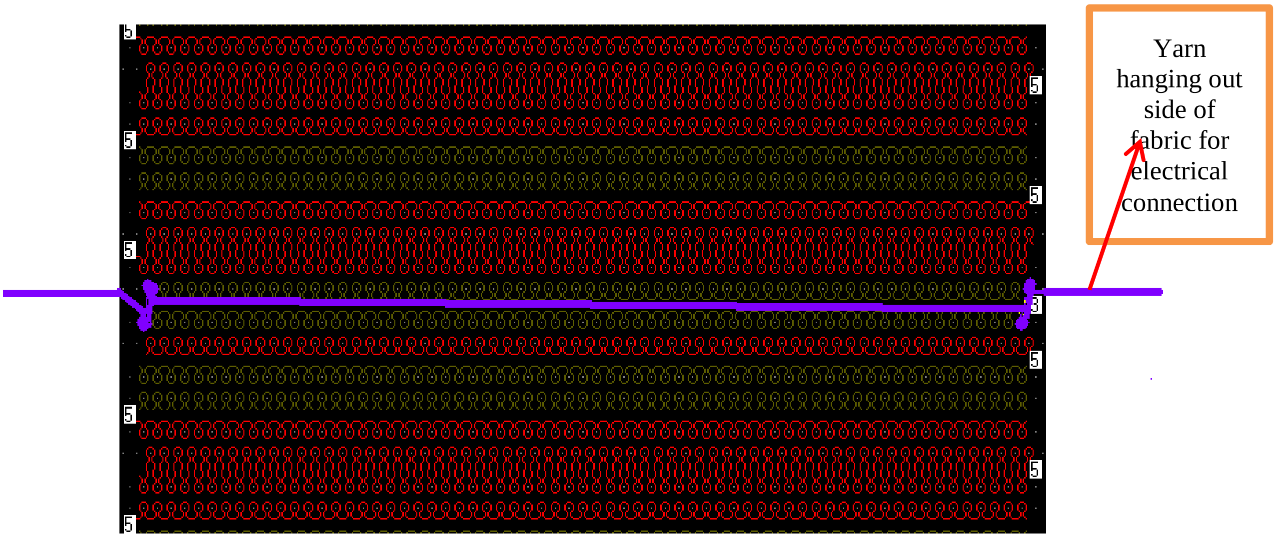


Figure 3 G-KSD 1, Stainless steel yarns knitted at the end to avoid yarn slippage and yarn left outside the fabric for electrical connections.

The G-KSD 2 was produced by laying in two layers of Stainless steel yarn as shown in the figure 4. The first layer of conductive yarn was laid in between 13th and 14th course from left to the right direction of the machine. It was laid back in from right to the left direction between 17th and 18th course of knitted structure. As shown in the figure 4, both ends of the conductive yarn were on right hand side for connection purpose.

The same problem of slackness of embedded yarn as was observed in the first design (G-KSD1). Similarly, it was resolved by carefully stretching the yarn.

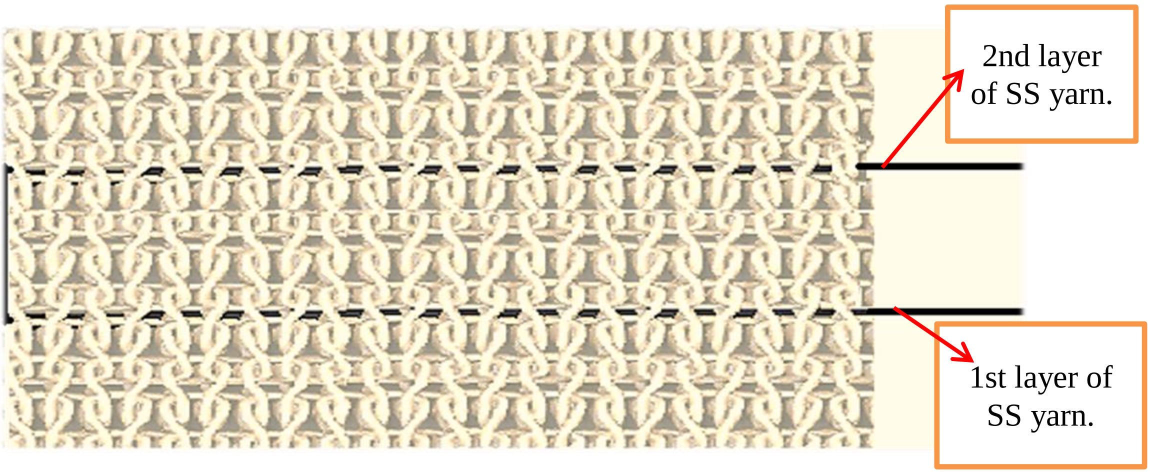


Figure 4 G-MKSD 2, two layers of Stainless steel yarn laid in

The third sensor design was produced by knitting stainless steel yarn in the middle of the sample. It was knitted between in the middle of the sample at around 25 mm of total sample width (50mm). The location of sensor was exactly as that of sensor design one. The contacting points would be responsible for change in resistance as shown in the figure 5.

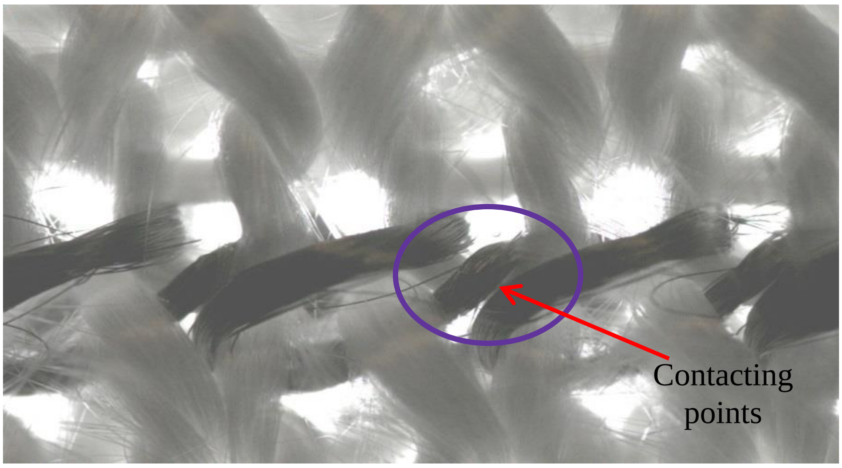


Figure 5 Stainless steel yarn knitted inside the fabric; photograph taken at 20X magnification by optical microscope.

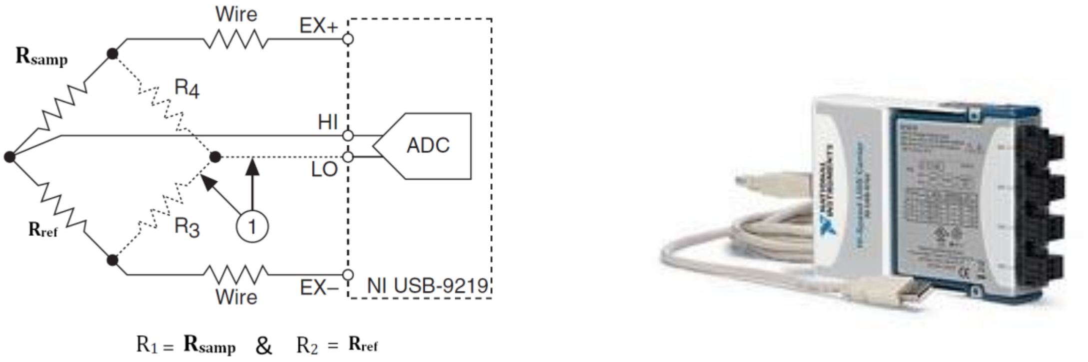
2.3.2.3 Electromechanical Characterisation

The sensing preforms were characterised for their strain sensing behaviour under electro-mechanical testing. The samples were subjected to tensile test and the change in resistance was observed simultaneously. The samples were tested on Zwick Roell/ Z050machine using 10KN load cell at a rate of 2mm/min. The gauge length was 100mm and pneumatic grippers were used to avoid slippage which was observed in the previous experiments. Six samples were tested for each types of sensor design.

For resistance measurement, the initial experiments were performed via four wire resistance measurement method on Agilent multimeter. However, a lot of noise was observed and the method of resistance measurement was changed to Wheatstone bridge circuit. National Instrument card (NI-usb-9219) was used to acquire the data by employing half bridge circuit. Each sample resistance was calculated initially by using fluke 115digital precision multimeter. An accurate resistor was selected for each type of sample with a variation of ±0.5 Ωs. The half bridge circuit was completed according the circuit diagram figure 6[a] by using National instrument NI-USB-9219.

The R_{sample}represents knitted sensing preform while R_{ref} is a resistor selected according to the sample resistance. Labview Signal express programme was used as an interface to acquire the signals data. The output voltage Vout/Vex-1/2 corresponds to NI-9219 reading. This reading was in mV/V and resistance was calculated by applying formula in equation (6) according to the instructions given in manual [62].

$$R_{sample} = \frac{R_{ref} - 2*NI_{9219reading}*R_{ref}}{2*NI_{9219reading}+1} \quad (6)$$



[a] [b]

Figure 6[a] Half-bridge circuit diagram with NI-9219,Full- lines representing external circuit while (1)-dotted lines represent the circuitry connected inside the 9219-module, source from National instruments [62] , 6[b] NI-Usb-9219**,** data acquisition card [63].

The data was collected separately and interpolation was performed through Matlab programme to correspond the resistance value accurately to the applied strain. The following figure 7 shows the data being collected in two separate data loggers.

[a] [b]

Figure 7[a] Electro-mechanical testing of knitted preform [b] Tensile and resistance data acquired separately.

3. RESULTS AND DISCUSSION

Table 2 Variation of Initial resistance ($R_{original}$) for three sensor designs

Sample resistance Ω	**G-KSD1**	**G-KSD2**	**G-KSD3**
Average resistance ($R_{original}$) Ω	9.6Ωs	16.2Ωs	41.6 Ωs

It can be observed that each sensor design demonstrated different initial resistance which was attributed to the total length of the conductive yarn. In sensor design one (G-KSD1), less yarn length was used as compared to the sensor design two (G-KSD2). Similarly, in sensor design three (G-KSD3) the length of conductive yarn was highest among the group because more length is required to knit as compare to laid in technique. Hence, the samples resistance increases with increases in yarn length within the sensor design. Therefore the results of initial resistance ($R_{original}$) of each sample satisfies equation (1).

The samples were stretched till 2.5% strain at 2mm/min and resistance change was observed simultaneously by half bridge circuit as explained in the methodology section. The sensor designs K-SD1 and K-SD2 experience change in resistance at an increasing order and it satisfies the theoretical aspect of strain sensor. The increase in resistance is synonymous to the sensor dimensions being changed under application of the force.

The relative resistance change of two samples exhibit approximately similar behaviour as shown in the figure 8. The sensor designs were tested up to 10 % strain to check for rupture. It was observed that a sudden increase is synonymous to cracking of the yarn. Therefore, a consistent pattern of resistance change was observed at higher loads. As shown in the figure 9, the sensor design 2 was stretched till 9 % strain and a correlation between higher load and resistance change is observed.

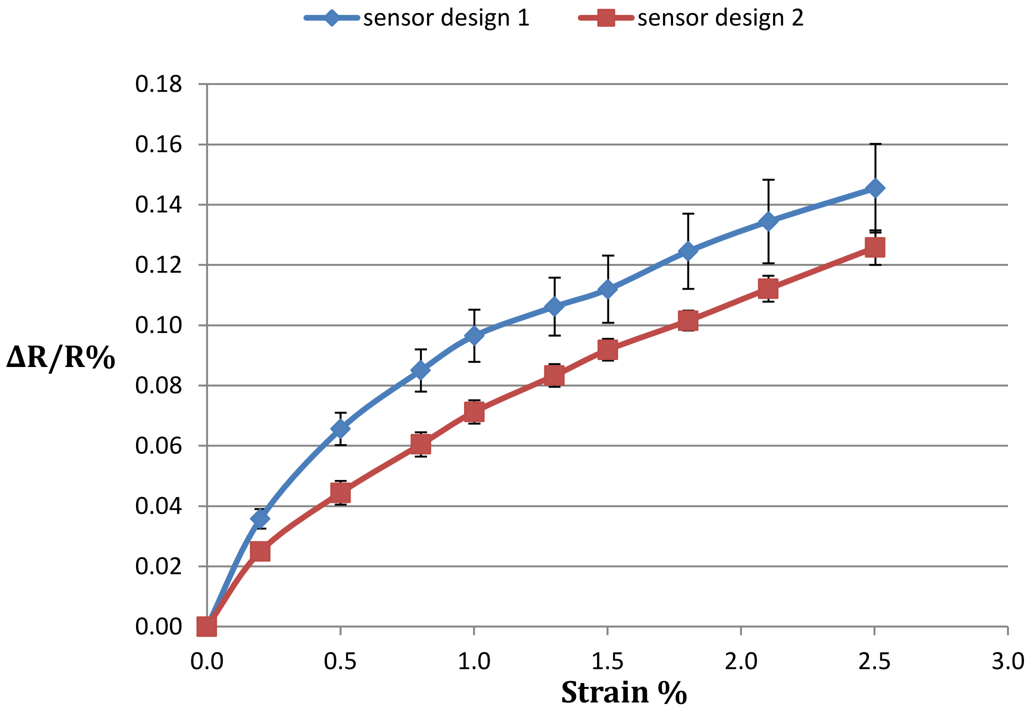


Figure 8 Relative resistance change behaviour under different extension regions of sensor design one (G-KSD1) and sensor design 2 (G-KSD3).

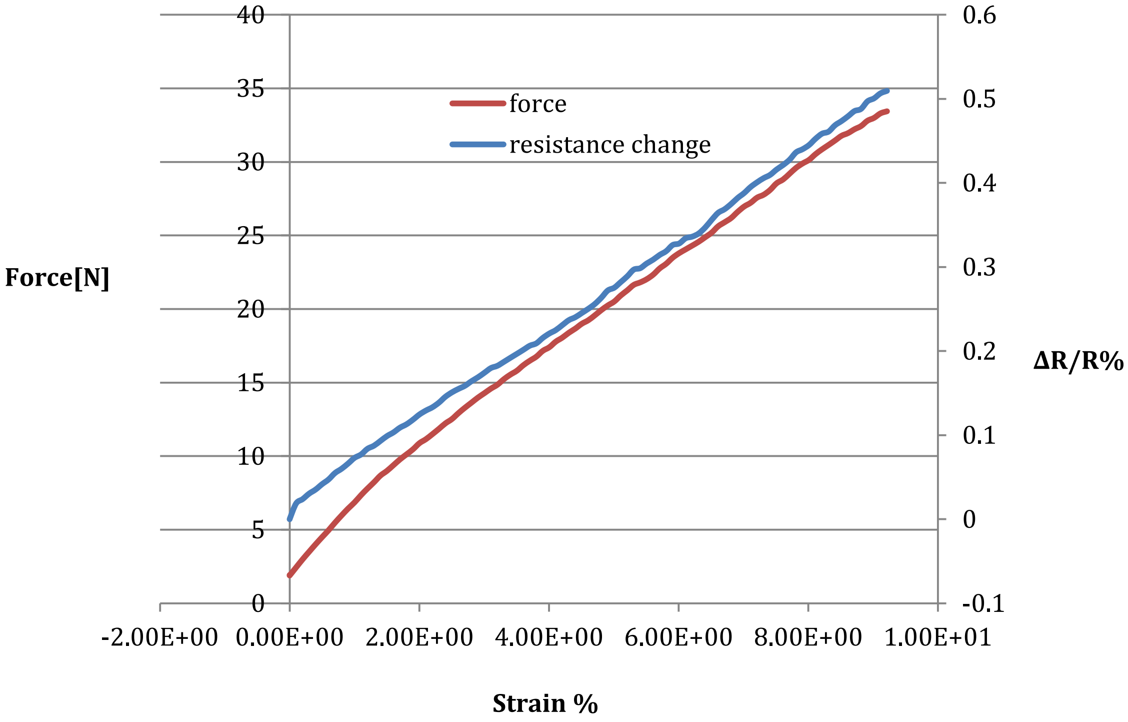


Figure 9 $\Delta R/R\%$ change with the increasing load till 9 % strain.

For sensor design3, a decrease in resistance is observed and it satisfied the fact that the contact resistance contributed towards decrease of the resistance. The sensor design (G-KSD1) and sensor design (G-KSD2) were also tested for cyclic testing within elastic regions and they followed repeatable pattern. However, within few sample resistance drift was observed. These samples experienced resistance change beyond the range of $(\pm 0.02\%)$ of elastic region. Within the elastic range $(\pm 0.02\ \%)$, the samples experienced no drift at all.
The gauge factor was evaluated for each type of sensor design till 2.5 % strain range. It was observed for three different regions of strain percentage.

1) 0-0.09%strain (Frist region)
2) 0—1% strain (Second region)
3) 0-2.5% strain (Third region)

The gauge factor was evaluated from the slope of the curve within each region and it was found to be highest within the first region (Elastic region). Sensor design1, Sensor design2 and Sensor design3 exhibit gauge factor of 0.24, 0.18 and 0.2 respectively in the first linear region. Within the second region, the sensor design 1, 2 and 3 experienced gauge factor of 0.08 and 0.06 and 0.06 respectively. Similarly for the third region the gauge factor of 0.05, 0.04 and 0.07 were observed respectively for the sensor design 1, 2 and 3. Therefore, clearly a lower gauge factor was observed with the increase in strain.

4 CONCLUSIONS

A preliminary investigation was performed to develop a functional preform and it was characterised under strain sensing by using half bridge circuit. A weft knitting process was utilized as a tool to integrate sensing yarn at the preform manufacturing stage. Following conclusions can be drawn from this study.

1) A sensing/functional layer can be created successfully by employing weft knitting process. This would reduce the hassle of integrating at the composite manufacturing stage. Furthermore, the location of sensor can be optimised during preforming.
2) The sensing layer was characterised in preform prior to the resin infusion. This approach would ensure any sensor design modifications are possible prior to the composite manufacturing process. This will reduce the time and cost associated with the composite manufacturing process.
3) The functional layer was analysed for its electromechanical behaviour up to larger extensions levels due to the fact that a flexible composite structure would also experience the same behaviour.
4) The gauge factor was evaluated and it was observed that the sensor sensitivity reduces at larger extension regions. The reason is attributed to the sensor design as sensor experienced irreversible resistance change at higher extension regions. In order to increase the gauge factor at higher strain %, the sensor should be able to behave elastically in those regions. Therefore, the sensor design should be modified to increase the sensor sensitivity.
5) The relative resistance change is very small and a very precise measuring setup is required to achieve the signal data. Wheatstone bridge circuit was found to be the best option for the measuring resistance changes.
6) The connection type had also great impact on the quality of signals. It was found that smooth signals were observed using terminal blocks as compared to crocodile clips.

5. FUTURE WORK

The future work will involve characterisation of multifunctional flexible composites by using the same methodology. Furthermore, new sensor designs will be created to increase the elastic range of the glass preform. In this regard, weft knitting process will be utilised to create a highly flexible glass knitted preform.

6. ACKNOWLEDGEMENT

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