Mechanical Performance Evaluation of Fiber Composites Equipped with In-Situ Wireless Sensor Bodies

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Abstract

In modern day structural engineering, fiber-composites play a vital role for their capability for light-weight construction and high stiffness value. More and more applications are being developed in various industries ranging from science, architecture and engineering. These structures can also be equipped with multi-component sensor systems for different performance evaluations both during pre- and post-curing processes. In this work a novel method is developed to place wireless sensors inside the fiber reinforced composite system to enable multifunctionality without much trade-off in mechanical performance.

Key objective here was to optimize the sensor shape to minimize stress accumulation and crack propagation around the sensor geometry inside the cured composite sample under stress. A finite element simulation model is developed for this purpose and a parametric model for the sensor geometry provided better insight into the force distribution along the fibers around the sensor element.

Consequently, different testing sample combinations were prepared, for which, fibers were either cut or bend around the sensors and dielectric channels. Various composite samples with different shapes of sensor dummies were also experimentally tested to validate the computational results. CT scan models of post-cure samples before and after loading enabled in-depth understanding of fiber alignment that could cause disturbances in overall mechanical performance. The scan models also provided with sufficient information about unwanted porosity, and micro-crack growth inside the composite under loading, which turned out to be vital for establishing a reliable simulation model and improving parameters in manufacturing process.

In the end, the goal of the work was to transport the know-how of such production unit from experimental and flexible manufacturing system like vacuum assisted resin infusion (VARI) to more sophisticated processing systems like prepreg manufacturing where all necessary information can be provided as inputs prior to the impregnation, thus removing error occurred due to manual handling.

1 Introduction

According to current research, the global market size of composite is predicted to reach over US$ 163.14 billion by 2030. The reason being the increasing use in different applications for growing markets for composite materials. Beyond major application industries like aerospace and automotive, composite structures have found their place among various other applications starting from heavy industries like wind turbine and civil constructions to specialized applications like biomedical engineering and robotics.

With increasing use-cases, structural integrity of composites has become a prime focal point of research in recent past. Structural behavior of composite materials is mostly classified as their response to different mechanical loadings. These responses vary depending on the quality of composite, which in turn depend on the final state of the reinforcing fiber and the structural behavior of the resin matrix obtained during curing process. Hence, a significant amount of research has been dedicated to in-situ curing process monitoring to ensure higher quality and reproducibility in fabrication [1,2].

Historically, there have been different methods deployed by various researchers to investigate curing characteristics, optical fiber grating [3-5] tools and dielectric methods [6-8] being prominent among them. In the later, a sensor system is directly integrated into the composite structure, monitoring the curing process by measuring dielectric properties of the resin. Developments in chip-less sensors also enable wireless measurement and operation in GHz range. Integration of such sensor within the composite layers is enabling the producer to monitor wireless the curing process locally in the area of interest apart from providing information on variations of process parameters across the thickness. Predecessors to this work [9] looked into this very topic to accommodate a rectangular shaped sensor inside a fiber composite. One major problem faced during the development was the effect of sensors in the local integrity of the composite due to resin accumulation around the sensor. This work attempts to push the idea one step further to integrate a sensor body within a sandwiched layer of fiber composite via either cutting or bending of fibers, thus avoiding resin accumulation along the edges of the sensor body. The findings encouraged this work to investigate further into the shape optimization of the sensor body for better integration.

2 Methodology

2.1 Materials

To prepare an elaborate study on the subject, we had to have different combinations of case studies. Thus, we chose to test both glass fiber and carbon fiber composites. Initial case studies were focused on glass fiber composites. For this purpose, unidirectional glass fibers of type HP-U400E and bidirectional X-E-1212 type of fibers were considered. Major takeaways from glass fiber composites were extended to carbon fiber composites for which C300U-1220 type of fibers were used.

For the resin system, we used commercial EPIKOTE™ Resin MGS® RIMR 135 with curing agent EPIKURE™ Curing Agent MGS® RIMH 137 at recommended mass ratio of 100:30. To realize the effect of sensors in structural integrity, actual sensors were replaced with 3D printed dummies with exact dimensions. For this purpose, we used ANYCUBIC i3 Mega S FDM printer with PLA filament material.

2.2 Manufacturing process

The required specimen with/without sensor dummies were manufactured in the form of plates using VARI method and were later cut according to standard test requirements. The advantage of using VARI method over other manufacturing methods is that, it provides flexibility for experimentation with the shape, and quality by adjusting fiber volume content. While fiber volume content of all specimen was kept constant at 50% the forms differ based on requirements.

Fig.1 shows a typical set-up of infusion process. After infusion, the plates were kept at 25 °C (room temperature) for 24 hours followed by post-curing process which was performed at 80 °C in an oven for 15 hours.

Fig. 1: A typical VARI infusion process set-up for composite manufacturing

3 Results

3.1 Initial case-study

To fully realize the scope of this work, we first constructed a set-up with a representative dummy model embedded inside a glass fiber composite consisting of bidirectional fibers. To simplify the process of computation, a rectangle shaped dummy was printed keeping thickness equivalent to original sensor i.e., 500 μm. The ply arrangements of four conceptualized testing samples are illustrated in the Fig.2.

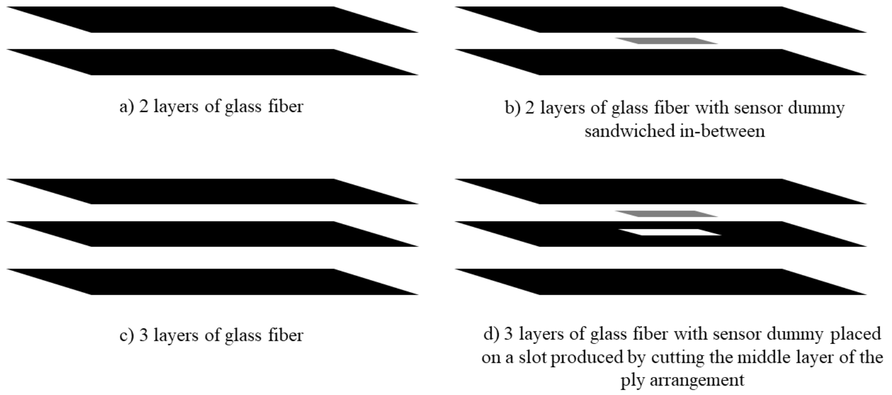

Fig. 2: Ply arrangements for initial case-study

Once plates were prepared, samples were cut for tensile testing to be carried out on a ZWICK 1445 universal testing machine, which has a capacity of ±100 kN. Accordingly, a standard norm DIN EN ISO 527-4 was followed with specimen length and width being 250 mm and 25 mm respectively, with sensor dummies always being at the center of each specimen. For each test case five samples were prepared and tested to determine the statistical distribution of test results. All tests were carried out at constant room temperature and tensile load was applied with a displacement control mode at the rate of 2 mm/min. The aggregated comparative force-displacement curve is shown in Fig.3.

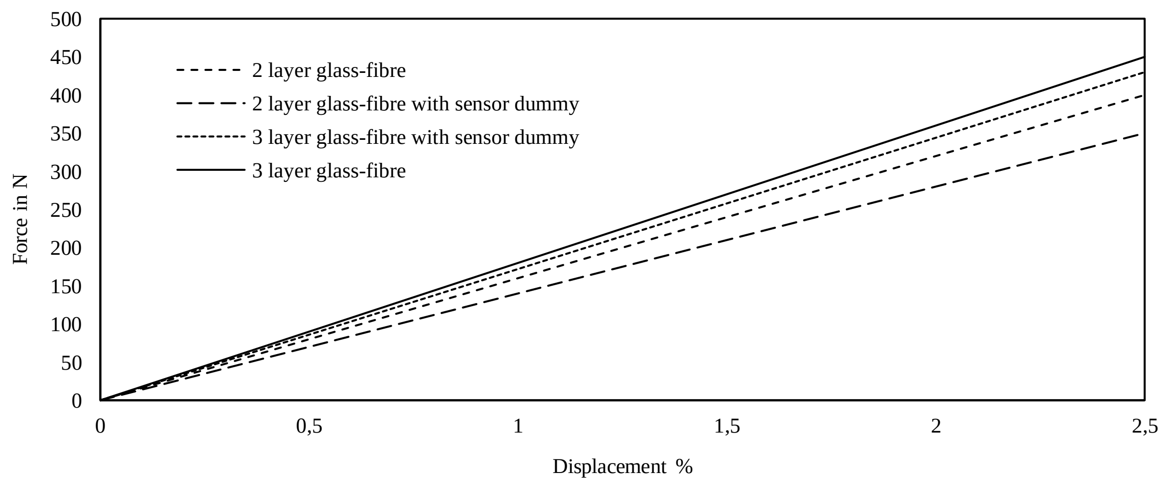

Fig. 3: Force-displacement curves obtained from tension testing

From tension test results, it is obvious that 3-layer composite perform by a higher load in comparison to 2-layer composite due to the presence of an additional layer of glass fiber. It is also evident that integration of sensor dummies minimizes strength of each composite system, as the fiber-resin matrix loading path is disturbed due to the presence of a foreign body. Interestingly, degree of reduction in strength within 2-layer composite system due to the presence of the dummy is almost 8% higher as compared to similar modification in the 3-layer sample.

To investigate the results further, finite element models were constructed mimicking similar testing set-up using ABAQUS CAE solver. Each layer of composite was modeled according to standard material property provided by the manufacturing and the lamina was stacked with appropriate material orientation to represent bidirectional behavior. Each contact pairs were labeled separately and ‘tie constraint’ as contact definition was enabled. To reduce computational time, a standard hexahedral mesh type C3D8R was chosen. To mimic tensile test set-up, one end of the designed composite assembly was kept fixed while the other end was allowed to move only in the length-direction. A representative force of 100N was applied on the loading end and specimen models with dummy sensors were examined.

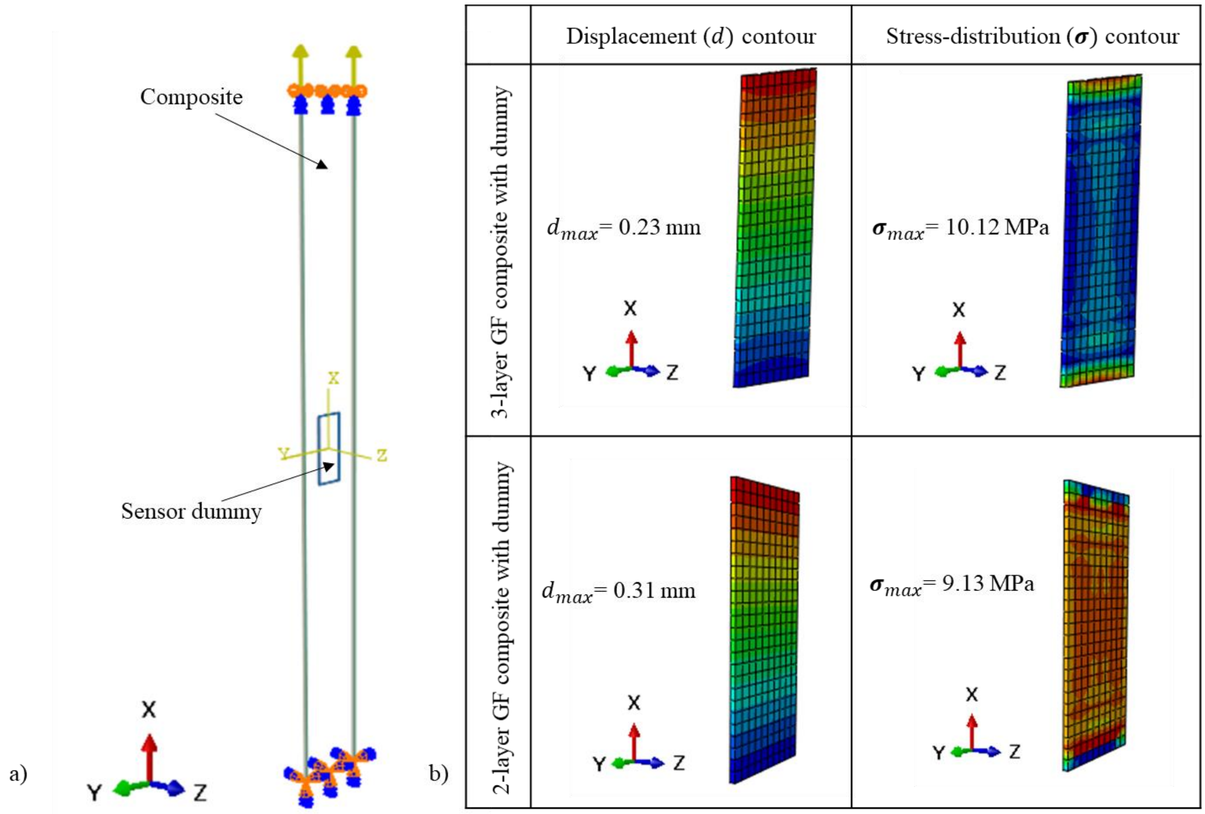

Fig. 4: FE modelling: a) Geometrical modelling set-up, b) Relative comparison of stress and displacement on dummy in two different test cases (increasing from blue to red)

From obtained results, it can be safely concluded that the sensor accommodated within a glass-fiber layer experiences less deformation compared to one where it is sandwiched between two layers. Although stress values in such case are marginally high, but distribution of maximum stress is only at the edge of the sensor body in contrast to 2-layer GF sample, where the entire sensor body experiences maximum stress value, thus being more prone to crack resulting in structural and functional failure.

3.2 Sensor shape optimization

From previous experiment, it is clear that the contact region between sensor and fiber layer experience higher amount of stress in the embedded model. This is due to the fact that force-lines along the fibers need to bypass sensor body (contrary to straight lines in standard composite sample) as illustrated in Fig.5.

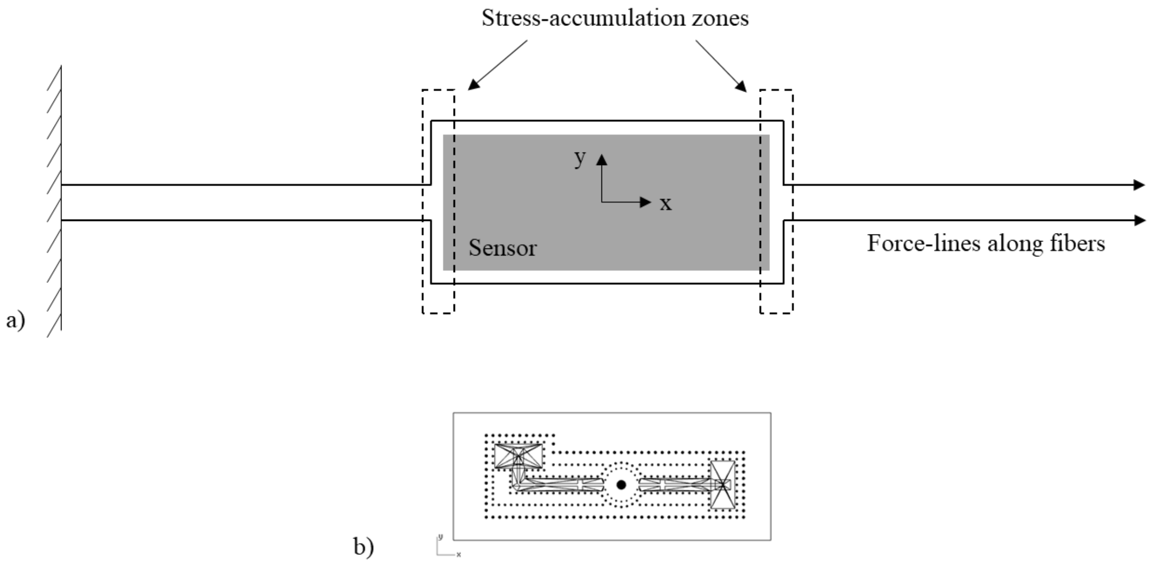

Fig. 5: Modelling process: a) Illustration of force-line and stress-accumulation zone, b) component distribution inside actual sensor

Avoiding multiple stress-accumulation zone is very essential to secure structural integrity. To achieve the goal a parametric representation of the model was constructed within Rhino Grasshopper visual programming domain. The idea was to optimize the shape of the sensor body to smoothen the force-lines. Lower bound of the optimization process was the minimum area defined by electronic components within the sensor while upper bound being maximum expandable shape of the sensor without drastic change in the mechanical performance of the composite.

For modelling purpose, a bunch of points were located on the boundary of the sensor body, which worked as control points to generate force-lines at different off-sets. These were essentially NURB curves wrapping the sensor body, with one end fixed and other pulled along major axis of the curves to replicate tension test set-up. Kangaroo Physics, a toolbox inside Grasshopper governed by particle-spring method, was used to calculate energy of deformation along each curve which worked as optimization function. The goal being minimization of energy, Galapagos, an evolutionary optimization tool, was used with previously generated control-points being design variables. Keeping design constraints in check, an elliptical shape was finalized as shown in Fig.6 as a locally optimized shape for sensor dummy for further investigations.

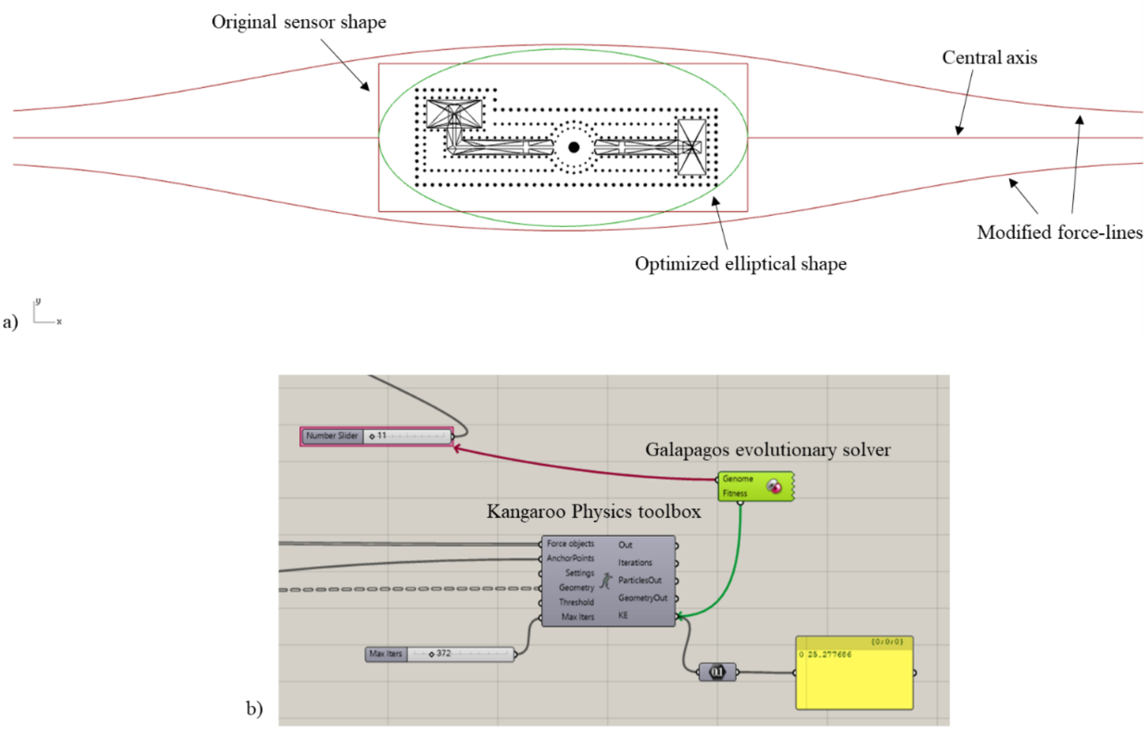

Fig. 6: Parametric modelling process: a) Illustration of optimized shape and force-lines, b) snapshot of specific tool boxes used in the modelling process

Using the modified shape in the frame-work of FE simulation mentioned in Section 3.1 immediately shows the contrast between rectangular and elliptical dummy. The stress regions drastically reduced, indicating less deformation under loading.

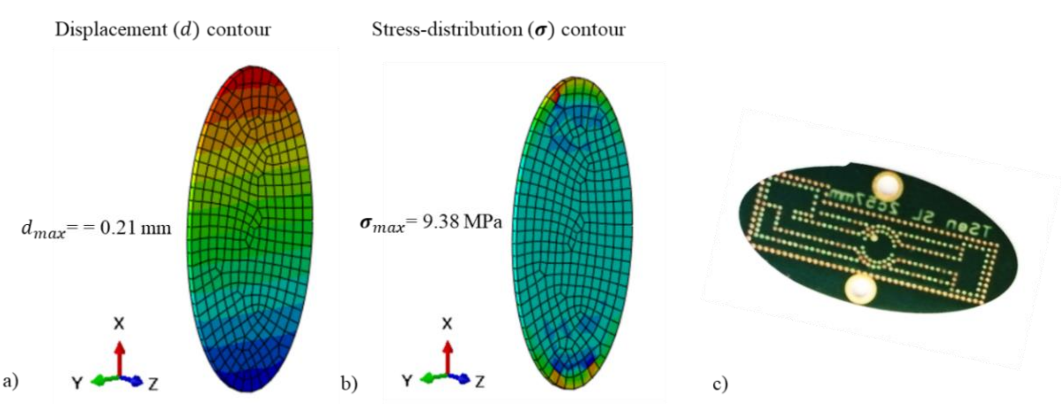

Fig. 7: FE simulation of elliptical dummy: a) displacement contour, b) stress-distribution contour (increasing from blue to red), c) manufactured modified sensor

3.3 Crack simulation

To simulate and predict crack-growth, cohesive zone modelling in ABAQUS was adopted which allows to model entire assembly as one single model and material properties can be assigned locally to specific region. This in turn avoids any error occurred to contact constraints. Moreover, only the layer of interest, i.e. mid-layer of the composites with the sensor dummy was modelled for computational ease. Both rectangular and ellipse models were tested for crack initiation and propagation with XFEM method.

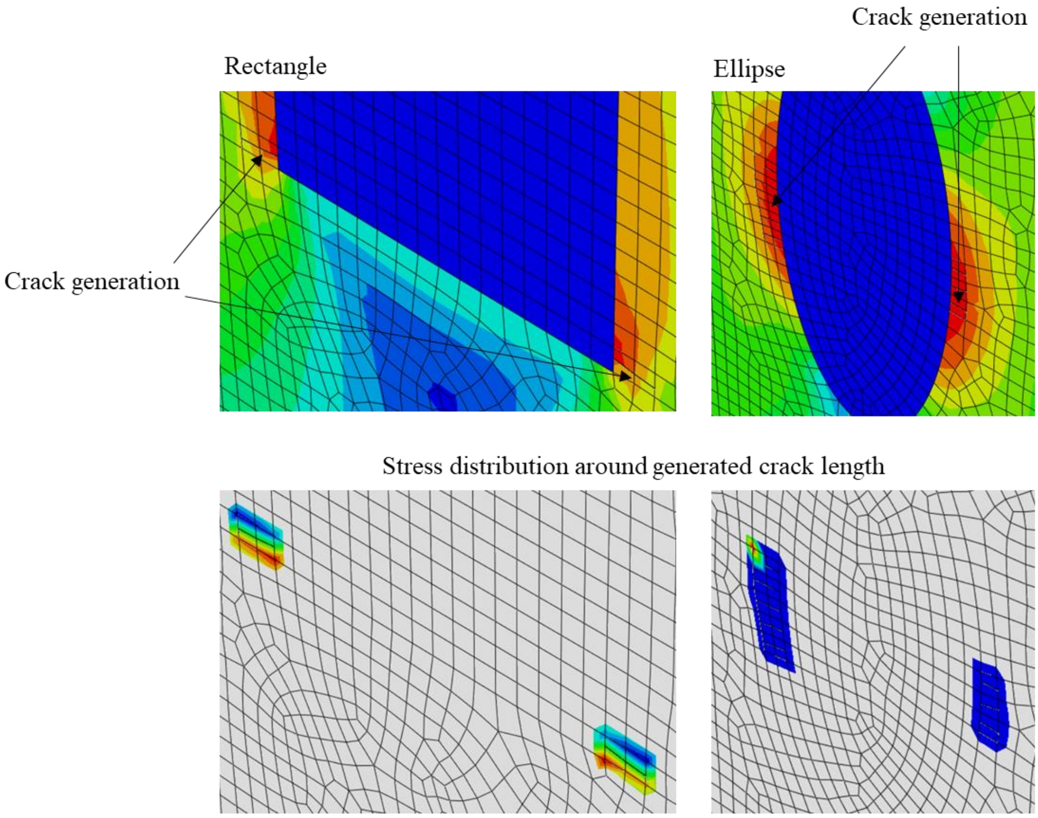

Fig. 8: XFEM crack simulation comparison

As it can be seen from Fig.8, cracks in the model with ellipse shaped dummy were around the obtuse curve of ellipse surface, mostly being minor cracks in length while a handful of elements of the model undergoing severe deformation due to crack propagation. While in the case of rectangular shaped dummy, cracks occurred along sharp corners on the opposite edge with larger length.

3.4 Further improvements and modifications

Once sensor shape was finalized, they were further modified with dielectric channels which works as reflective path for antenna embedded inside the sensor. Dimensions of channels were kept minimal to effect structural integrity of the composite system. Further discussion on the channels are beyond the scope of this paper. To mimic these modifications accurately, dummies were also modified and printed accordingly as shown in Fig.9 for further case studies.

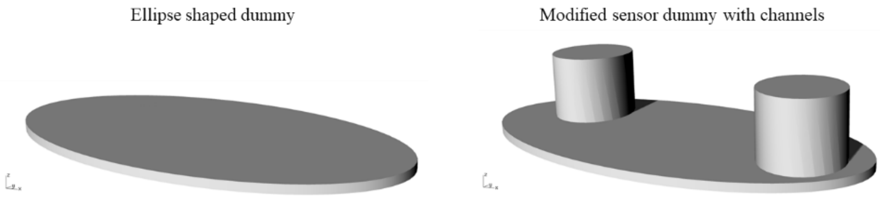

Fig. 9: Modification in sensor dummy for further testing

Once modified, placements of dummies were further investigated. One set of samples were prepared by cutting slot at the mid-layer of fiber ply like previous test cases, while one different set of samples accommodated dummies via manually bending and fixing fiber yarns in particular shape.

Both cases were examined for bidirectional glass fiber and carbon fiber composites separately and also evaluated against respective composite samples without any external body. Tension test results aggregated over five specimens for each test cases are illustrated in Fig.10.

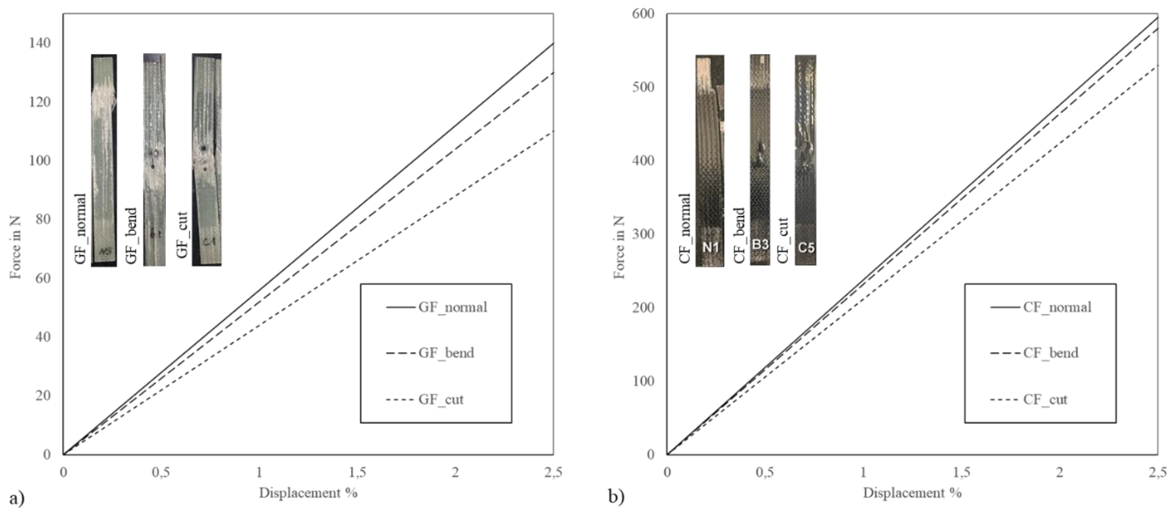

Fig. 10: Tension test results with representative tested samples for: a) unidirectional glass fiber composite, b) unidirectional carbon fiber composite

With cut-samples there is a noticeable decrease in composite strength when compared with bend-samples, which wasn’t evident in tests performed in Section 3.1. The higher resistance provided by bend-samples both in glass and carbon fiber composite can be credited to the fact that in such samples, fibers do not loose continuity in force-line.

One more reason for low strength in cut-samples can be attributed to displacement of dummy sensor from the assigned slot due to resin flow while manufacturing, which can be avoided in bend-samples as the dummy is transversely sandwiched between fiber yarns.

To investigate this issue further, one glass-fiber cut-sample was scanned before and after tension test using computed tomography method. Results shows a clear displacement of the dummy from the assigned slot. Although evidences were limited to only one instance, the results were in accordance with simulation models concerning crack-generation and growth.

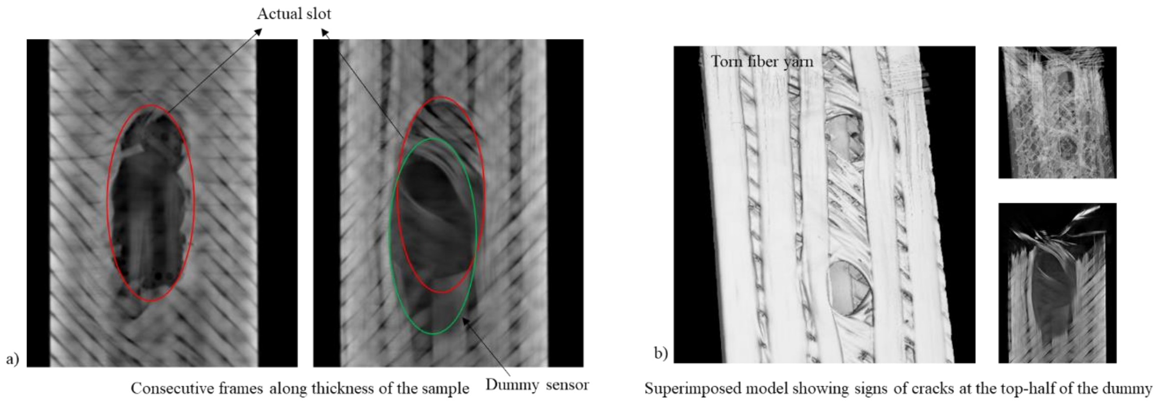

Fig. 11: CT-scan results: a) instances of misaligned sensor dummy placement due to experimental error, b) signs of initial crack due to tension test

4 Conclusion

Overall goal of this project is to successfully integrate a dielectric sensor inside a composite to investigate by wireless sensors the characteristic behavior during the various curing processes. To achieve the goal, it is important to understand the structural impact of such systems. Thus, in this part of the work, we limited our investigation within structural deformation domain. We found that shape of sensor plays a significant role in the overall structural deformation. We conceptualized various case-studies to find causes and tried to improve on existing technology. A parametric model with evolutionary solver was used to optimize the shape of the sensor. Various analytical and experimental studies were done to understand the behavior of such embedded sensors in composites both in glass and carbon fiber domain. It was found that bending fibers to accommodate sensor body instead of cutting fiber layer or sandwiching sensor within two layers of fiber, results in improved structural behavior. In the end CT-scan models were investigated to understand limitations of experiments. Further improvement in shape optimization and scan models would result in better understanding of such systems, which would be necessary to replicate such methods in other industrial manufacturing processes.

Acknowledgements

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