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Advanced Space Systems Enabled by Fiber Optic Sensors: Rocket Propulsion Systems Application

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PhD SST Space Science and Technology

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Introduction

The design of modern spacecraft systems and launch vehicles is more oriented towards reducing system-level assembly, integration, testing, and qualifications complexities while aiming at raising the systems' performance. In order to maintain high overall system performance while reducing these complexities among others, the use of smart materials and structures is of rising interest to advanced space systems' designers. This study discusses a well-known concept: smart space structures made of carbon fiber composites embedded with Fiber Optic Sensors (FOS), with a focus on their applications in modern spacecraft. The concept and applications referred to are nowadays sought-after for utilization in several modern spacecraft and launch vehicles design concepts, made feasible by various technological advancements. First, the significant progress in manufacturing techniques such as additive manufacturing and advanced composites manufacturing. Secondly, the emergence of the photonic integrated circuits technology realizing the miniaturization of the FOS data acquisition systems (i.e., interrogators). This technology and its miniaturization enable the employment of FOS systems in harsh space environments and a myriad of spacecraft designs. A case study on rocket propulsion of spacecraft is presented that considers the employment of FOS in the structure and propellant storage of propulsion systems to advance their operational and condition monitoring (OCM) as well as the structural health monitoring (SHM) and integrity, towards realizing the new generation of intelligent spacecraft propulsion. The study identified a number of possible future applications and assessed their employment feasibility in lights of the current technological advancements' challenges and foreseen opportunities. In addition, a novel mathematical strain-transfer model is presented to serve the proposed fiber optic sensors' embedding technique in carbon fiber structures of spacecraft.

Methodology

The activities carried out in this research were achieved by a multi-disciplinary research approach by connecting and combining expertise from the fields of: (a) Photonic and Fiber Optic Sensing Technology; (b) Materials Science; (c) Spacecraft Composite Structures; (d) Space Systems Engineering; (e) Rocket Propulsion Applications. A rather comprehensive literate review was implemented, scoping the identification of the applications of fiber optic sensors in space as well as the challenges and barriers imposed by the interrogation systems from one side, and the FOS arrays embedding from the other. The focus was narrowed down to number of academic and industrial high-impact applications that can be employed fully or partially as case studies. Smart Propellant Tank and Smart Spacecraft Structures were the two main applications considered for the case studies due to their aforementioned impact, besides their prototyping feasibility. There was a critical need to address the gap in literature concerning the clear definition of an FOS embedding method to simplify the measurands interpretation while not sacrificing the data interpretation and variables prediction integrity. Hence, in collaboration with expert on nano-materials, the group was able to derive a novel strain-transfer mathematical model aimed for composite pressure vessels and thin-walled panels of composite fibers material applications.

FEM was used to generate the Maximum-Principal Vector Maps for a given structure, as seen in following figures, according to the proposed embedding and placement method coupled with the introduced novel opto-mechanical strain-transfer analytical model. A comprehensive discussion was provided on this aspect in section 3 of our publication [1].

Prototyping activities initiated early March 2024, for the Smart Propellant Tank, and Smart Isogrid stiffened structural element using advanced composites manufacturing methods and employing novel FOS embedding techniques. After the sensors' characterization campaign completion, a more clear-understanding will be drawn on the FOS strain-transfer model calibration.

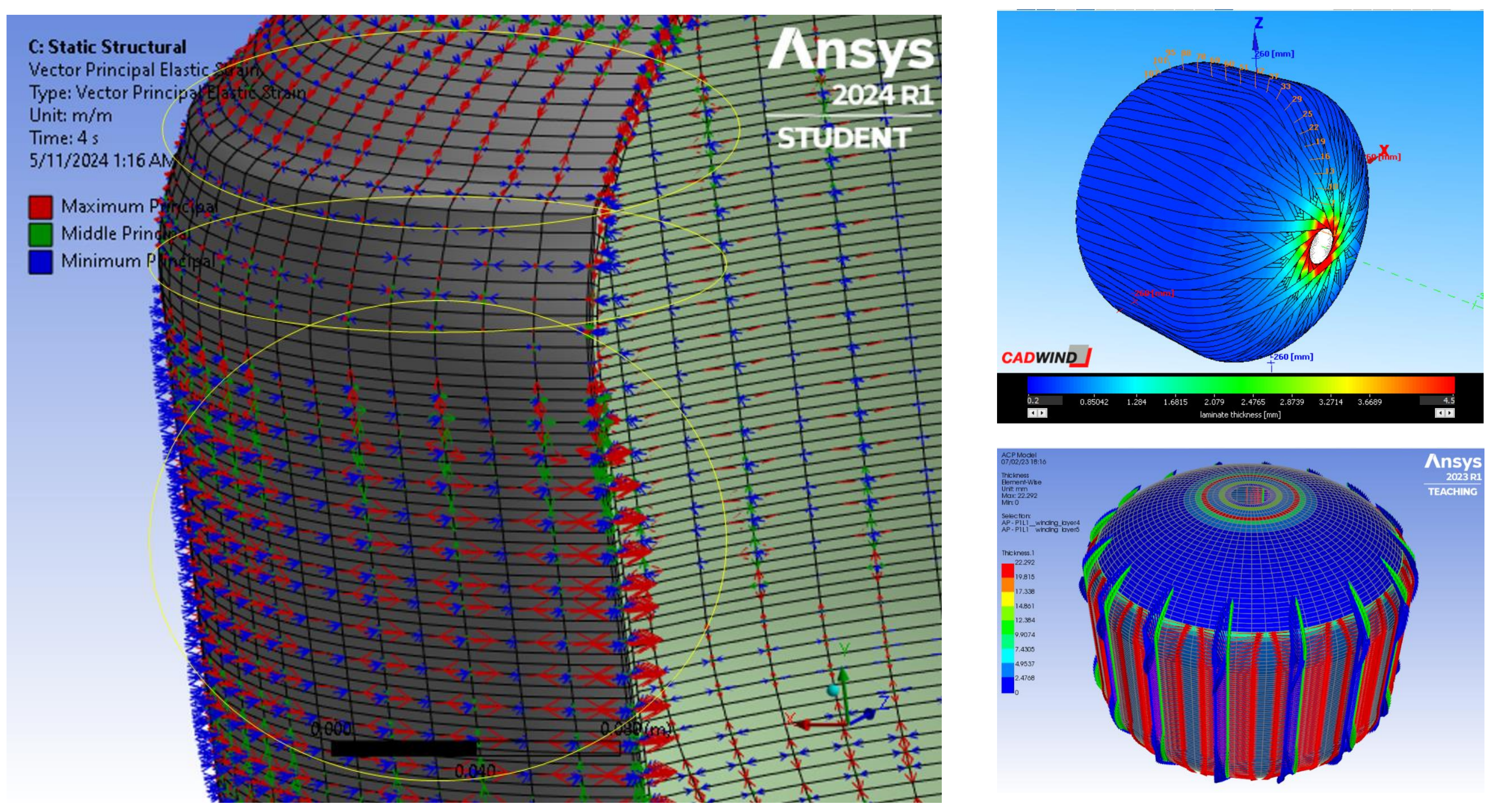

Fig.1 . Graphical representation of the Vector Principal Elastic Strain highlighting three regions of the pressure vessel (i.e., Smart Propellant Tank). Referring to [1] for the in-depth discussion.

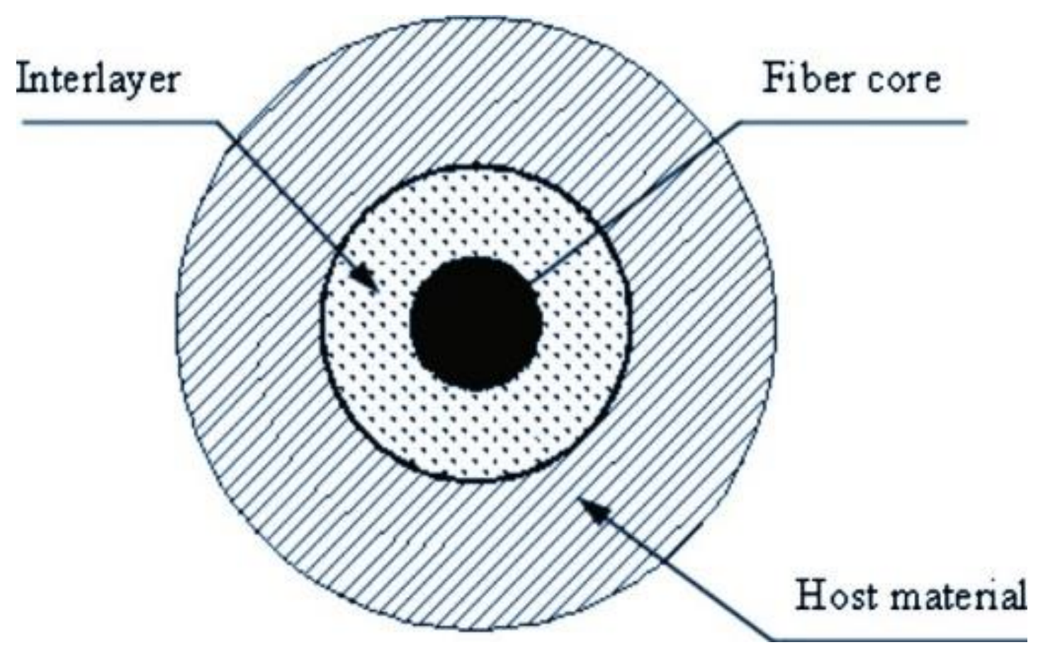

Figure 2. Embedded optical fiber sensor model cross-section. Adapted from [2].

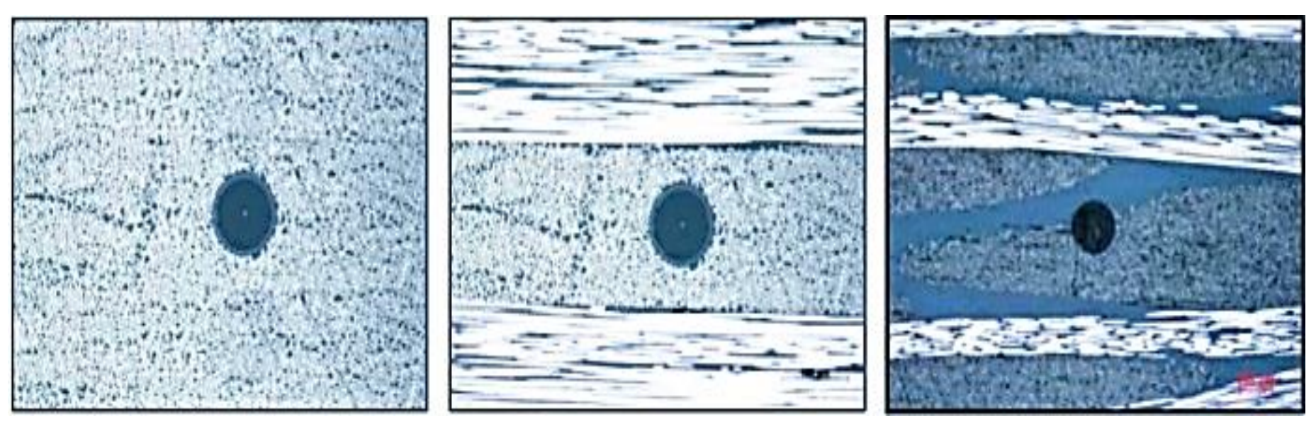

Figure 3. Embedded optical fiber sensor cross-section in different fiber composite orientation. From [3] as cited in [4] under Creative Commons.

Discussion and Conclusion

Unlike the conventional approach mostly placing orthogonal sensor elements in redundancy, it is proposed that: ***"an optical fiber array of FBGs or a backscattering-based optical fiber sensor can be embedded or surface-mounted placing the sensing element in a direction parallel to the direction of the relevant local maximum principal strain on the structure in hand considering the loading conditions and the boundary conditions during the system operation."*** – the ***maximum principal strain direction*** is believed to be reliably and easily predicted using the design simulations employing finite element methods and further validated through experimental tests. Please refer to Section 3 in[1] for complete discussion and derivation.

$$\sigma_{Max\ Principal} \equiv \sigma_1$$

$$= \frac{E\left(\frac{\Delta\lambda}{\lambda} - C_T \Delta T\right)}{(1-\nu^2)\left\{1 + \frac{1}{2}n^2[p_{12} - \nu(p_{11} - p_{12})]\left(1 - \frac{cosh(kx)}{cosh(kL)}\right)\right\}} - \frac{(\alpha_{i,c} - \alpha_{i,f})\Delta T\left(1 - \frac{E_f}{E_c + E_f}\right)}{(1-\nu^2)}$$

- Despite the maturity of FOS technology utilization in space applications from a conceptual aspect, it is still unemployed in spacecraft systems due to, mainly, (a) limited acquaintance by the space systems community with FOS technology and its associated capabilities in spacecraft applications and harsh space environment; (b) lack of adequate documentation, as suggested by the literature reviews [5] [6], on reliable FOS embedding techniques in spacecraft systems and structures.
- Although the 1st generation of FOS interrogation units were proven successful onboard small-satellites (i.e., PROBA-2 Mission 2009-2013), and the subsequent 2nd and 3rd generation have proven success in preliminary tests of rocket re-entry (i.e., ESA ROTEX-T Demonstration 2019/20), it is believed that the current advancements in Photonic Integrated Circuit (PIC)-based interrogation systems will play a crucial role in the transitioning from conventional sensors technologies to the new photonic and fiber optic sensing in space applications, attributed to their intrinsic ultra high-speed, low-power, superior miniaturization, and immunity to electromagnetic interference, among others.
- Several current technological challenges associated with extended in-space storage of cryogenic propellants and its boil-off, e.g., of in-orbit refueling scenarios of SpaceX Starships for interplanetary missions, are believed to be strongly impacted by FOS technology providing superior OCM of the storage and refueling systems in-orbit through the FOS multiple point temperature mapping.
- Employment of Q-DOFS and/or DOFS in spacecraft applications will advance the capabilities and reliability of spacecraft OCM and SHM and will help overcoming several technological challenges associated with in-orbit operations, propellant gauging, as well as fluid-phase change identification.
- FOS and high-speed interrogation will open new opportunities to employ AI-based signal processing for advanced parameter prediction in modern spacecraft applications.

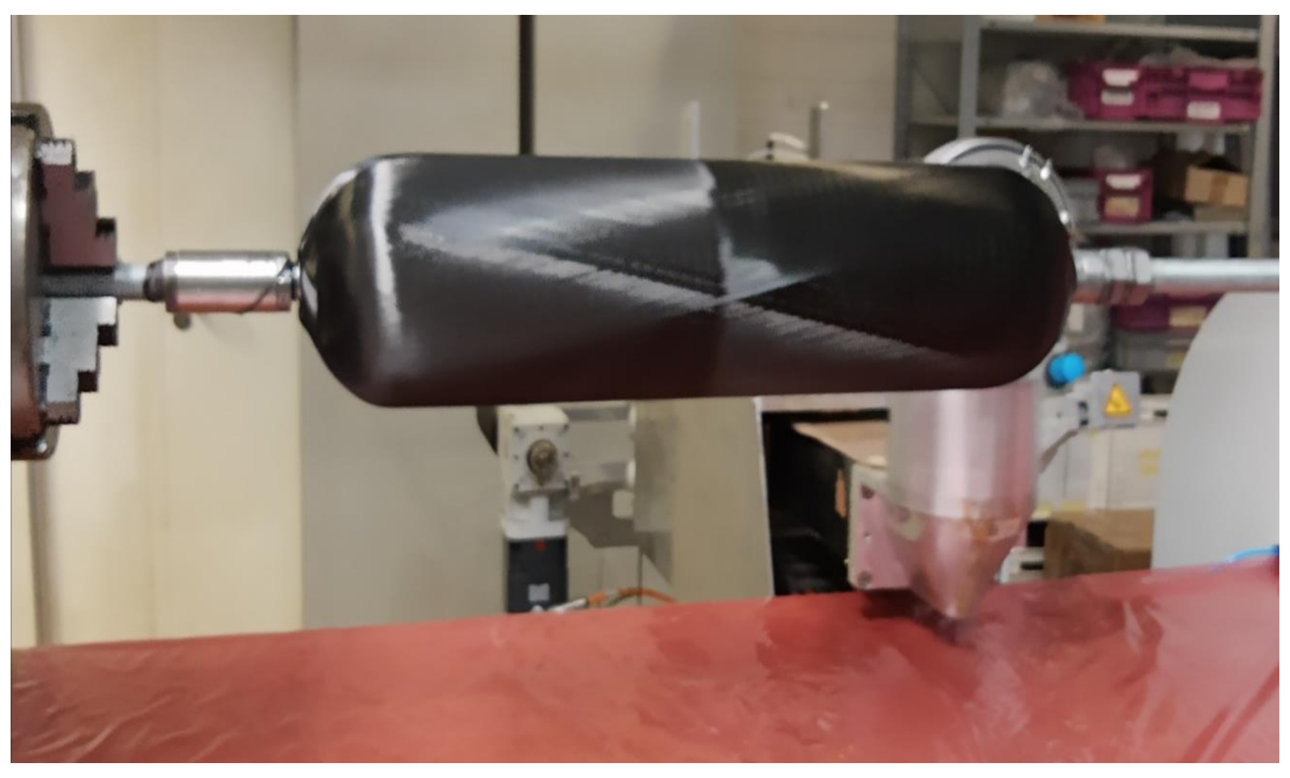

Fig. 4. Smart Propellant Tank carbon fiber filament winding in facilities of TUM (May 2024) – currently ongoing prototyping process.

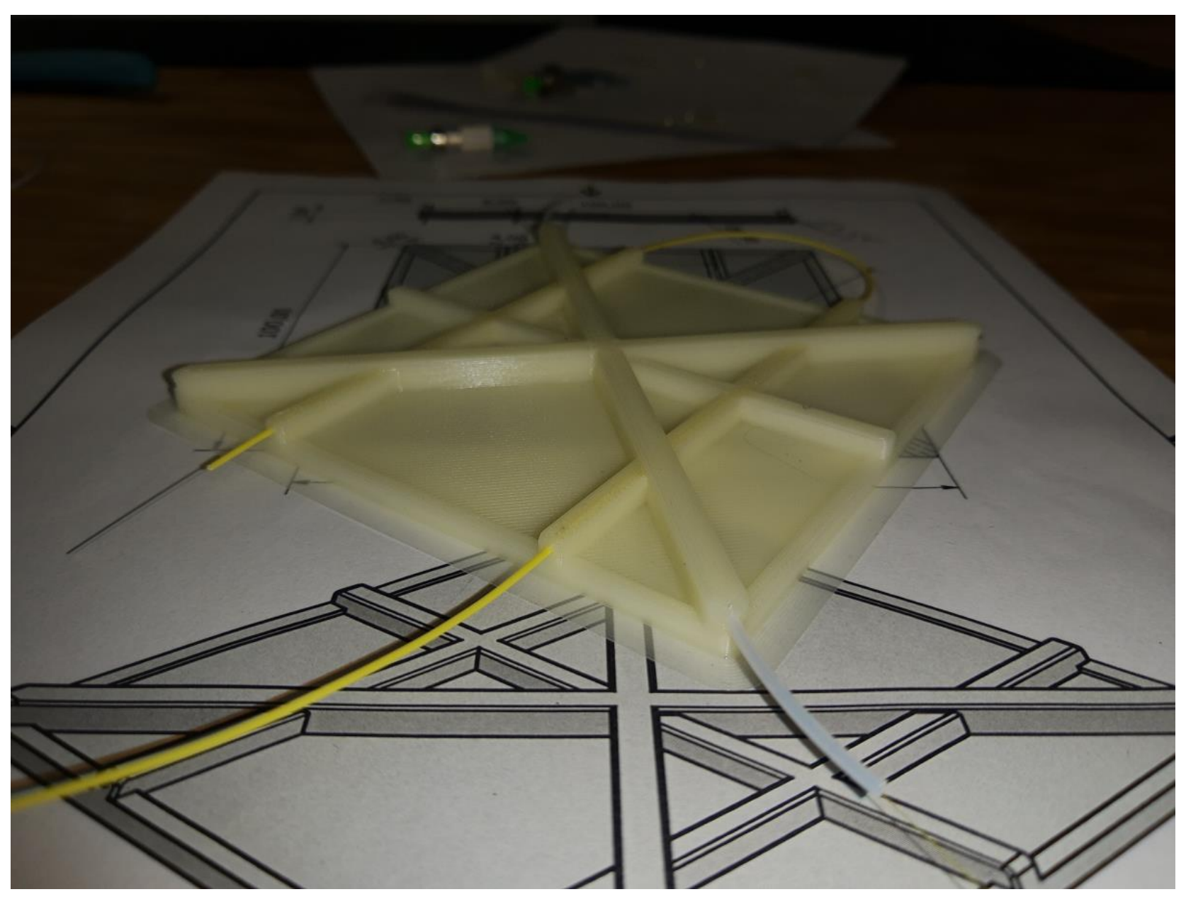

Fig. 5. Smart isogrid stiffened plate element (10x10 cm^2) embedded with FOS array in Yellow loose tube (Φ 0.9mm, PP); White ingress/egress tubes (Φ 1.6mm, PTFE). Structure of Nylon by GEWO Performer 260 industrial 3D Printer in TUM (May 2024).

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