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Combining Additive Manufacturing Techniques for High-Performance Stiffened Panels

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Abstract: Additive manufacturing of high-performance thermoplastics including high temperature materials and continuous fiber reinforcement are extensively being developed worldwide. In this work, we combined laser-assisted insitu consolidation tape laying and fused filament fabrication to manufactured in three stages to manufacture 100% thermoplastic stiffened panels with innovative designs using LMPAEK-PEKK carbon fiber reinforced polymers. Overprinting of gyroid structures on top of ATL laminates assisted by laser shown very good adhesion. Mechanical testing by flatwise and four point bending tests show tensile strength in the range of 10MPa (flatwise) and 889MPa (four-point bending). Tomography analysis shows the optimization roadmap to enhance mechanical properties by improving temperature management during manufacturing.

Keywords: Additive manufacturing, laser-assisted in-situ consolidation, automated tape laying, fused filament fabrication, gyroid stiffeners, flatwise, four point bending test.

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1. Introduction

Additive Manufacturing is envisaged to revolutionize the composite structures value chains by widening their design space, lightweight potential and deployment of multifunctional materials which are reversibly processed, enabling disassembly, multifunctionality and repair [1, 2, 3]. Among all AM techniques for high-performance composite structures, aviation sector looks closely to automated tape laying and fused filament fabrication techniques due to their ability to produce structural parts with commercially available materials [4]. However, there is the need for a more systematic process optimization based on data, as well as controlling the manufacturing parameters along the whole process, which is an intrinsic challenge for this kind of out-of-mould manufacturing processes [5]. In this work within DOMMINIO Project, we present the combination of laser-assisted automated insitu consolidation tape laying (ISC-ATL) of LM-PAEK carbon fiber-reinforced tapes and fused filament fabrication (FFF) of neat PEKK to manufacture next-generation multifunctional stiffened panels. A first set of structural planar cupons (500x500) were manufactured consisting on quasi-isotropic planar laminates and overprinted gyroid-based stiffeners using a digitally integrated manufacturing cells, gathering key thermal data during manufacturing of such structures. Manufacturing optimization shows the importance of thermal history of thermoplastic materials in their crystallization, warping and interlayer adhesion, both for the ISC panels as well as for the stiffening gyroid elements, for which laser heating systems show to provide the needed energy density to enhance LM-PAEK to PEKK adhesion strength by 2x. The first set of stiffened panels were mechanically tested following flatwise structure standard (ASTM C297) to characterize the tensile strength of the bonding interface between ISC panels and FFF gyroids, showing values up to 3.1MPa, as well as four-point bending test (ASTM D6272-17) to characterize the flexural strength achieving 3.554 MPa based on interlaminar failure of the gyroid layers and a tangent modulus of elasticity of 162 GPa.

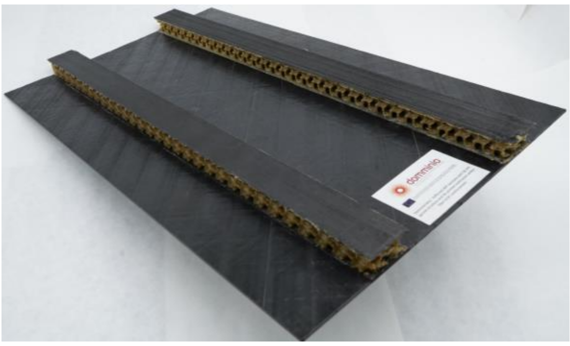
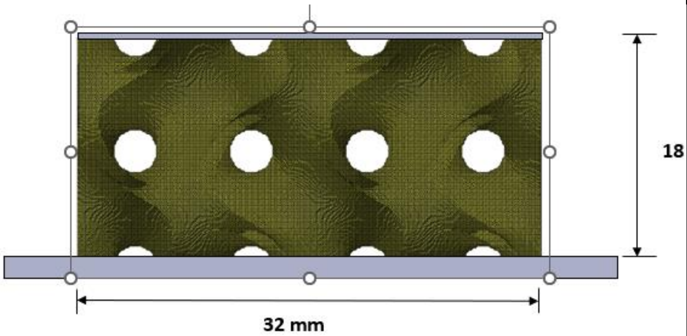
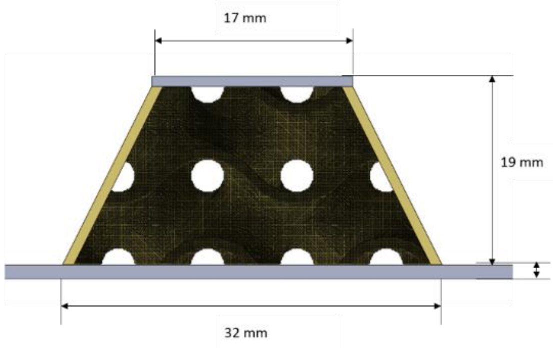
2. Experimental

Manufacturing of two stiffened panel and testing conditions are discussed below.

USE CASE 1: The laminate was manufactured with CF/LM PAEK tape, with 16 layers on a quasi-isotropic distribution, following this lay-up: [-45 / 45 / 0 / 0 / 90 / 90 / 45 / -45]s. After the skin has been manufactured the stiffeners were printed on top of the laminate using PEKK polymer, and for the first layer adhesion a laser system was used on the head of the robot to solve the problems related with the layer adhesion. To increase the stiffness of the overprinted gyroid structure, a layer of continuous CF/PEKK at 0° was printed by FFF. An exemplary video of the manufacturing of this demo can be found in this link.

USE CASE 2: In this configuration the main difference is the trapezoidal geometry of the stiffener and the top reinforcement. In this case, to increase the stiffness of the stiffener, a top reinforcement was manufactured by ATL, having a total of 8 plies and the following lay up: [45 / -45 / 0 / 90 / 90 / 0 / -45 / 45]. The result of one of the prototypes manufactured for this study case is shown in Figure 4.

Table 1 Stiffened Panels designs and main manufacturing parameters.

<table>
<tr><td>USE CASE 1</td><td>USE CASE 2</td></tr>
<tr><td></td><td></td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2"><u>ATL parameters LM-PAEK:</u> Laser-assisted sin-situ consolidation, Speed: 250 mm/s, Compression force: 500 N, Temperature: 400°C.
<u>FFF parameters PEKK</u>: Nozzle Tª: 370°C, Printing speed: 20mm/s, Laser preheating temperature: 350°C.
FFF parameters <u>CCF-PEKK (Only use case 1):</u> Nozzle Tª: 390°C, Layer height: 0.4mm, Printing speed: 10mm/s, Laser power: 7.5W, Laser preheating temperature: 350°C.</td></tr>
</table>

Structural demos presented were mechanically tested, starting with a flatwise test to quantify the adhesion between the ATL laminates and the FFF gyroids, and following with a four-point bending test of the whole structure.

Flatwise test: The flatwise test was carried out under ASTM C297 to determine the plane tensile strength of the gyroid structure as well as the bond between the gyroid structure and the laminate, over 6 repetitions of 75x75cm coupons. Figure 1 shows a schematic of the configuration of the test samples. The specimens were manufactured using ATL to create an in-situ consolidated laminate of CF/LM PAEK tape with 16 layers. The layers were arranged in a quasi-isotropic distribution with the following lay-up sequence: [-45 / 45 / 0 / 0 / 0 / 0 / 90 / 90 / 90 / 45 / -45]s. On top of this laminate, a full polymer layer was deposited using FFF technology. Subsequently, a gyroid structure was printed on this polymer layer. To ensure good adhesion of the first printed layer to the laminate, a laser system mounted on the robot head was used.

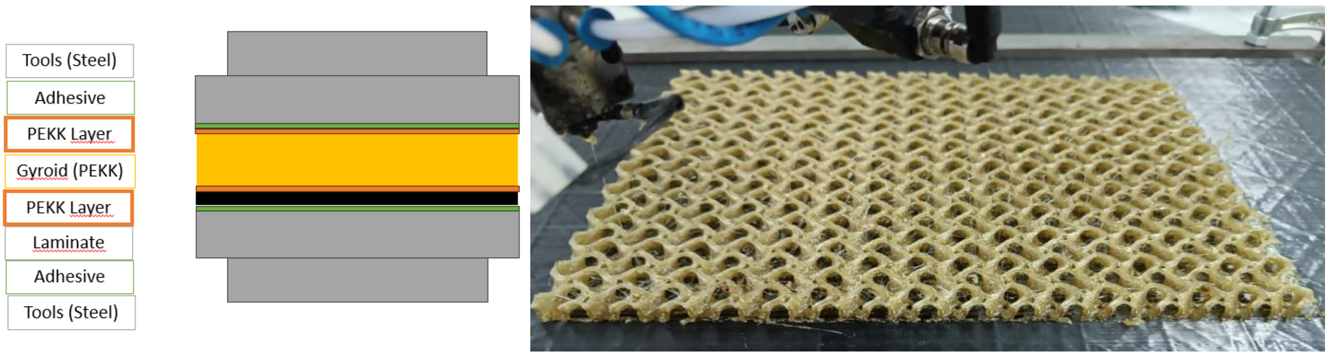
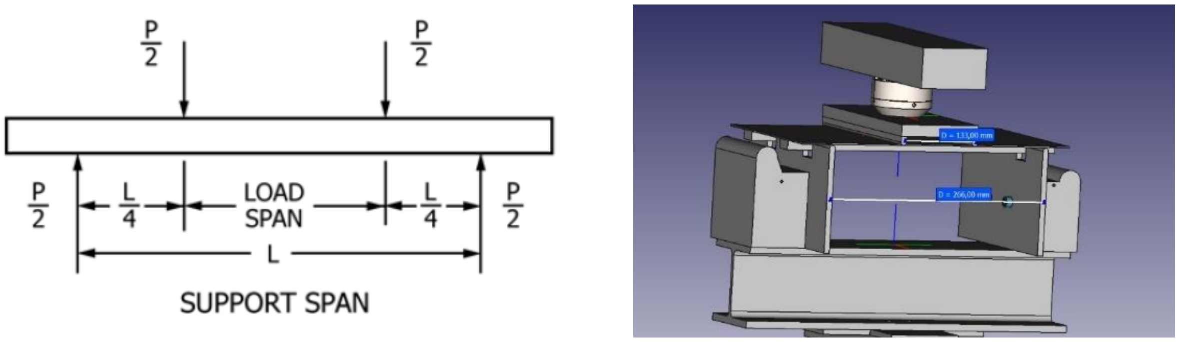


Figure 1. Schematic of flatwise test samples configuration. Flatwise specimen manufacturing process.

Four point bending test

All laminates tested (two repetitions for each use case) according to the ASTM 6272 standard, which outlines the procedures for determining the flexural properties of reinforced plastics. A SHIMADZU 5 kN testing machine (Model No. EENSTC_005, Serial No. 31080) was used. The experimental setup is illustrated in Figure 2. The setup included a support span (L) of 266 mm, a loading nose span of 133 mm, and a support span-to-depth ratio of 120. The supports and loading noses had diameters of 10 mm. The test was conducted at a speed of 1 mm/min until a preload of 5 N was reached, and then increased to 6.5 mm/min until completion. For this setup, the total thickness of the laminate and stiffeners combined was 21 mm. However, for assessing the bending behavior, only the thickness of the laminate, averaging 2.2 mm, was used as the depth of the beam. A key concern with this setup was the non-uniform thickness due to the stiffened elements. To address this, grooves were made in the lower supports to accommodate the gyroids, ensuring that contact was only made with the laminate. This approach aligns with the ASTM 6272 standard for determining flexural behavior.



aa) b)

Figure 2. Four-point bending configuration. a. Schematic diagram of experiment setup. b. Four-point bending test apparatus.

The tests were monitored using the following equipment: i) A potentiometer (Epromext, 50 mm, No. UMEM_011) placed on the bottom side of the laminate, 10 mm from the right edge, ii) an extensometer (Extensometer: 50 mm, No. HMEDEX_011) positioned at the center of the bottom side of the laminate, iii) strain gauges placed on both sides of the laminate. The gauges were attached to the laminates using Loctite EA9466 adhesive.

The loads applied during the four-point bending test applied to the stiffened laminates tested consisted on the following load sequence:

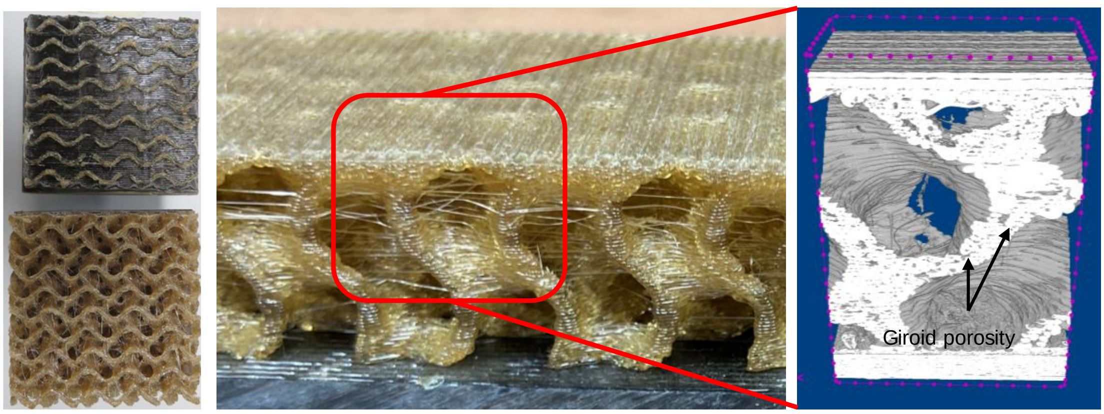
1. Preload at 5N / Load up to 700N / unloading
2. Preload at 5N / Load up to 700N / unloading
3. Preload at 5N / Load up to 1000N / unloading
4. Preload at 5N / Load up to 1850N, then continue up to breakage/ unloading
5. Load up to total breakage.

3. Results

Following the results obtained during test of the four stiffened laminates tested are detailed.

3.1. Flatwise test

The six repetitions of the flatwise test resulted on 17.413 ± 1.499 N, which is equivalent to 10,83 ± 0,93 MPa considering an effective planar area of the gyroid stiffener of about 28,57%. Cohesive failure mode of the stiffener core is observed (Figure 3a), which occurs within the core material itself and indicates that this zone is weaker than the bond between the core and the face sheets. Generally, only cohesive failures are accepted as valid failure modes in flatwise tensile tests. This is because cohesive failure within the core material indicates that the bond between the core and the face sheets is sufficiently strong, and the core material itself is the limiting factor in terms of strength. Cross-sectional micro-tomography was carried out on gyroid structures to analyse porosity distribution, as shown in Figure 3b-c below. As it can be observed in the middle and right image, gyroid manufacturing generated a large quantity of porosity between beads. This may be caused by low temperature deposition not enabling the as-deposited PEKK filament to properly flow. Despite the deposition temperature sufficiently reaches the melting point, the as-extruded material finds a cold substrate (in the range of 110ºC as compared to the extrusion temperature of around 400ºC), which may cause a rapid solidification of the extruded material, thus jeopardizing the proper flow and minimization of porosity.



a) b) c)

Figure 3. a) cohesive failure of PEKK gyroid, b) gyroid image and c) tomography zoom-in indicating porosity between beads in the gyroid, leading to cohesive failure.

3.2. Four point bending test

Below we discuss the results obtained during the four-point bending test of the stiffened laminates use cases for each of the load cycles detailed above. Figure 4 shows testing results and pictures of the stiffened laminate after being tested.

Stiffened laminate USE CASE 1-DEMO1&2. In both cases, the failure mode corresponds to longitudinal failure of the PEKK gyroid stiffener at al heigh of about 75% from the laminate surface in both demos. The carbon fibre laminate and the top CCF reinforcement did not presented delamination/failure.

- (**U1-D1):** At first some micro failures occur inside the gyroid structures until firsts visible failures as cracks in one of the stiffeners at 3600N of load and 5.1mm of stroke. The cracks within the gyroid structure continued to grow with increasing load achieving the maximum load at 3883N and 5.6mm stroke, reaching a flexural strength of 533,44 MPa.

- **(U1-D2):** The failure mode is similar than the obtained for U1-D1 stiffened laminate, cohesive failure mode at different levels of the gyroid structure. A crack/delamination appeared in the centre of one stiffener, between the carbon laminate and PEKK stiffener and it was propagated along it, generating a delamination in the middle of it. While stiffener 2 did not collapse. The maximum load is similar to the obtained for U1-D1, while the stroke is a little lower. The maximum load achieved was 4621N at 6.3mm of stroke, reaching a maximum flexural strength of 635,03 MPa.

Stiffened laminate USE CASE 2-DEMO1&2. Use case 2 showed 52% increased tensile strength as compared to Use case 1, leading to a different failure mode based on cohesive failure of the stiffener very close to the joint to the laminate, leaving behing the PEKK layer consolidated with laser to the ATL laminate.

- **(U2-D1)**: Figure 4 shows the pictures of the stiffened broken laminate at the end of the four-point bending test. In this case the failure mode is cohesive since it has failed between the first layer printed with laser against the laminate and the printed stiffener, although the breakage occurred between the printed structures and not at the join between the FFF and the AFP laminate. When the deformation is sufficiently high the stiffener fails transversaly, as it can be seen in the figure 4. This may be due to the increased stiffness of the gyroid structure by covering both side walls with a polymer layer. In this case, some cracking sounds began to be heard at 2800N, at 5000N the laminate cracks sound more and stronger and at 6200N the laminates finally breaks. The graph in Figure 4shows the maximum achieved load of 6133N occurred at a stroke of 5.8mm, reaching a maximum flexural strength of 842,66 MPa.

- **(U2-D2)**: Same failure mode as U2-D1, the stiffener failed by cohesive failure, it has failed between the first layer printed with laser against the laminate and the printed stiffener, the breakage occurred between the printed structures and not at the join between the FFF and the AFP laminate. In addition, the upper reinforcement by ATL laminate has been cohesively separated from the printed part in one of the stiffeners. When the deformation is sufficiently high the stiffener breaks transversasly. In this case, failure started at 5800N, although visually nothing was observed in the stiffened laminate. At 6803N the stiffener 2 breaks. At this point, the test is paused and unloaded to analyse the laminate status and then a final load is applied up to 5000N when the stiffener 1 breaks. As Figure 4 shows, both stiffeners broke in the central-finish part of the laminate, the stiffeners detached from the carbon laminate base, in the central area. The graph in Figure 4 shows the maximum achieved of 6803N occurred at a stroke of 5.5mm, reaching a maximum flexural strength of 934,65MPa.

Table 2. Four point bending test results.

	Maximum Load (N)	Flexural Strength (MPa)	Tangent modulus of elasticity (GPa)
ACIT-1	3.883	533,44	1282
ACIT-2	4.621	635,03	1257
ACIT	4252 ± 522	584 ± 72	1270 ± 18
BAE-1	6133	842,66	1456
BAE-2	6803	934,65	1476
BAE	6468 ± 474	889 ± 65	1466 ± 14

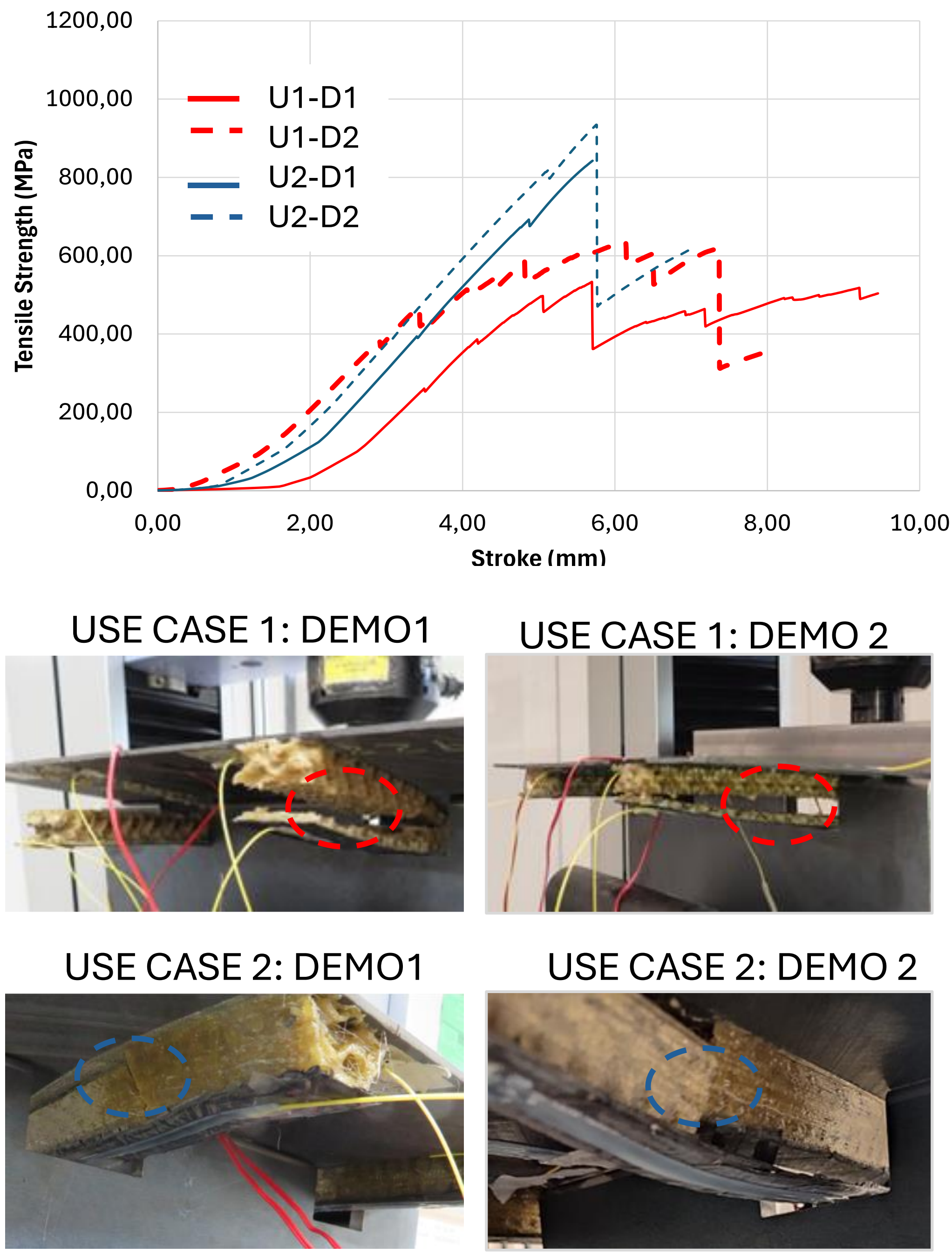


Figure 4. Four point bending test results (**a**) Tensile strength versus stroke; (**b**) Images of the tested laminates highlighting the different failure modes.

4. Conclusions

Two use cases (300 x 500mm) consisting of stiffened laminates combining laser-assisted insitu consolidation of LMPAEK tapes by Automated Tape Laying and overprinting of PEKK gyroids by FFF were successfully manufactured, demonstrating the feasibility of the combination of laser-assisted insitu consolidation ATL and FFF of high-performance thermoplastics (LMPAEK and PEKK), leading to intermediate-to-high mechanical properties up to 889MPa on four point bending test. Despite the good adhesion between overprinted PEKK gyroids and LMPAEK laminates assisted by laser, based on tomography analysis and mechanical results by flatwise, it is shown that there is still room for process optimization from the temperature point of view to minimize internal porosity and enhanced interlaminar adhesion. From the design point of view, it is shown the improvement on the mechanical properties by shifting to trapezoidal stiffeners with closed external walls and quasi-isotropic top reinforcement, as compared to quadrangular stiffeners and unidirectional continuous carbon fiber reinforce layer. Future work is envisaged concerning product temperature management (nozzle optimized design, embedded local heating on nozzle, heated table) and demonstrator

Supplementary Materials: The following supporting information can be downloaded at: https://www.youtube.com/watch?v=9usi16RtsSY

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study

Data Availability Statement: https://domminioproject.eu/, https://cordis.europa.eu/project/id/101007022

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