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INFINITE

Aerospace composites digitally sensorized from manufacturing to end-of-life

D6.3
Component approval and Aerospace certification guidance report

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2. INTRODUCTION

This deliverable report focuses on development of a test request which could be used to establish the basis for new material qualification. The development of the test request implies the definition of itself, as well as the execution of the test included on it.
This report has information related to all steps required to qualify a new material, such as materials, method of manufacturing, test campaign, testing conditions and results.
Possible differences on mechanical behaviour between reference and sensorised coupons are analysed in this report.

3. MATERIALS

3.1 NCF

Non-crimp fabrics (NCFs) are structures made of one or several layers of straight yarns laid upon each other and transformed into a fabric normally by a stitching process, through which they remain straight and free of any crimp. The specifications of the NCF, carbon fibre, binder and veil used in the projects are shown in Table 1.

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NCF DETAILS								
Style. Ply Sequence	CF Area weight [g/m²]	Single layer Area weight (CF) [g/m2]	Stitching pattern	Stitching length [mm]	Stitching yarn (Warp beam)			
Bidiagonal (0/90; 45/-45) Microwires 0°	Depending on layup: 480, 268, 200, 180, 150 gsm	Symmetrical (240/240)	TP(Trikot Pillar) for 0/90 P (Pillar) for +/-45	TP 4.0 P2.2	Y6 Co-Polyamide			
CF DESCRIPTION								
CF Classification	CF	CF Sizing	Diameter (µm)	Density (g/cm³)	Filament Count	CF Nominal Linear Density (tex)	Tensile Strength (MPa)	Tensile Modulus (GPa)
Standard Tensile Strength CF	STS40	F13- based	7	1.7	24K	1600tex	4300	250
BINDER (PB) (FOR PREFORMING PURPOSES)								
Type		Quantity[g/m²]		application on				
PB1: Epoxy Base (Hexion EP05311)		7 - 10 gsm (depends on final NCF style)		top or bottom				
VEIL (V) (FOR TOUGHING PURPOSES)								
Type		Quantity [g/m2]						
Veil (V6)		4						

Table 1. Specifications of NCFs materials.

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RESIN SYSTEM

For this project, a non-aeronautic resin system was chosen, specifically RESOLTECH 1050 and 1053S hardener. This selection was done because of two main reasons. 0n the one hand, on the date in which the resin systema had to be acquired, there were considerable problems in acquiring aeronautical resin systems, such as RTM6. On the other hand, the low level of TRL of the project enable choosing a resin system with non-aeronautical grade. Main properties of this resin are shown in Table 2.

Infusion temperature	Room temperature
Curing cycle	16 hours at 60°C
Tg	64°C

Table 2. Specifications of resin system.

4. METHOD OF MANUFACTURING

4.1 LAY UP

Different lay up's laminates have been used depending on the mechanical test to which they'd be subjected. It is important to remark that, for almost all tests, the lay-up tested does not meet with the one required by the applicable standard. This is because available standards refer to conventional laminates, such as unidirectional tapes or wovens. No specific standards for NCF were found to be used in this project.
Because of this, the lay-up was defined taking into account recommendations from TEIJIN and the head manager of the Mechanical testing laboratory from TITANIA.
Laminates have been manufactured by manual lay-up, in IDEKO's facilities. The manufacturing process consists on different steps: cut of layers, manual lay-up, compaction, vacuum bag and curing in oven.

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Figure 1. Images from manufacturing process performed at IDEKO. Up: Manual lay up process. Down: Vacuum bags before curing.

4.2 CURING CYCLE

According to the technical data sheet of the resin system, the curing cycle to be applied to the is shown in Figure 2.. The curing cycle implies a free heat up to 60°C, and keeping this temperature for 16 hours. There is not a heating-up and cooling-down rate defined for this curing cycle. Figure 2 shows the register of the curing cycle performed at IDEKO.

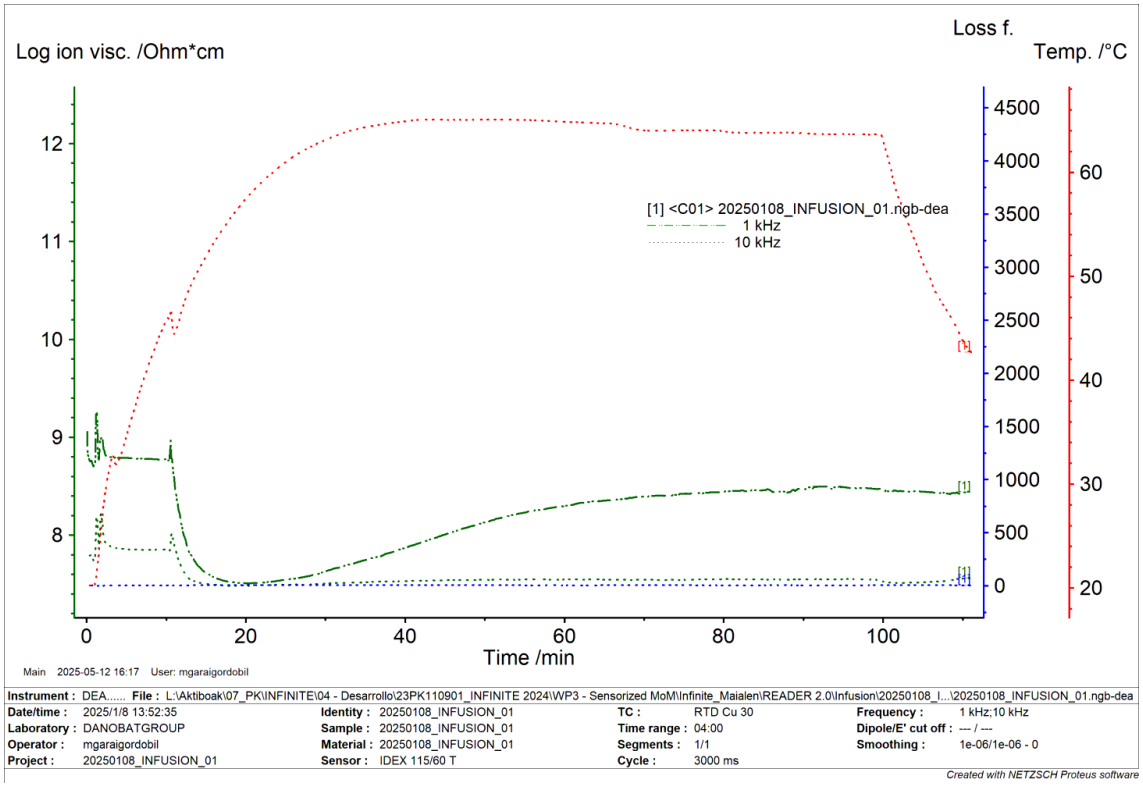

Figure 2. Register of curing cycle performed at IDEKO.

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4.3 TABBING

The use of tabs for mechanical tests has been studied at the beginning of the test campaign. For some tests, the use of tabs may be necessary because of dimensions of the coupons (specially thickness), geometry of them and expected loads.

After a first analysis performed by the Laboratory manager of the mechanical testing laboratory of TITANIA, it was concluded that the use of tabs could be necessary for tensile and compression tests, for plain coupons.

The selection of the adhesive to be used for tabbing step was a critical issue, since the use of the adequate adhesive is determinant to obtain the desired results. Due to the low Tg temperature of the resin used in INFINITE, it has been difficult to find an adhesive which presents good mechanical behaviour with low curing temperature. After an in-depth search, it was decided to use the adhesive Araldite 4858.

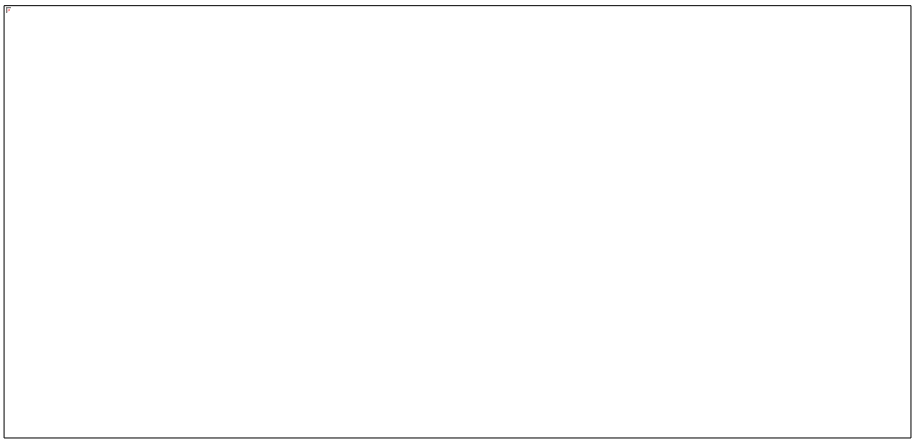
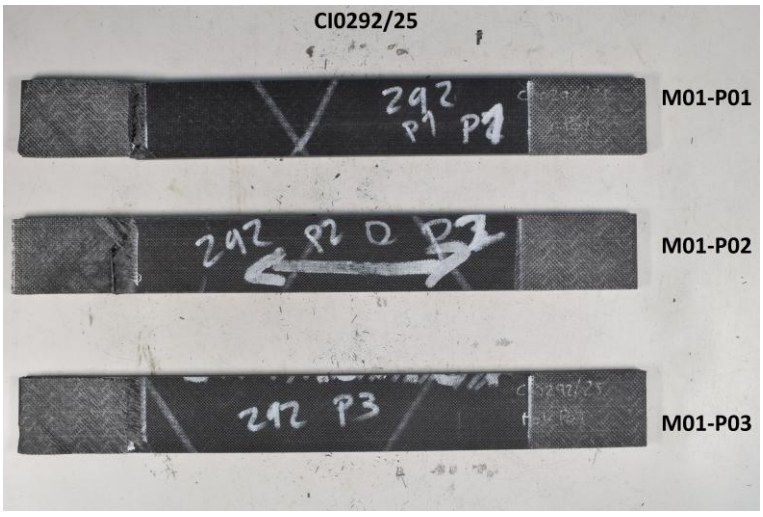


Figure 3. Shear strength versus temperature for the adhesive used for tabbing, Araldite 4858.

According to the shear strength behaviour of the adhesive as function of temperature, Figure 3, it can be observed that the properties of the adhesive are reduced with temperature. Taking into account that high temperature tests would be performed at 50°C, it was concluded that the adhesive will not support the expected loads for tensile and compression tests. Before discarding the performance of these tests, it was decided to tests coupons without tabs. Figure 4 shows the failure mode observed after testing indicates that the coupons presented invalid breakage. This means that the use of tabs is mandatory for these tests. Thus, it was decided not to perform tensile and compression tests at high temperature.



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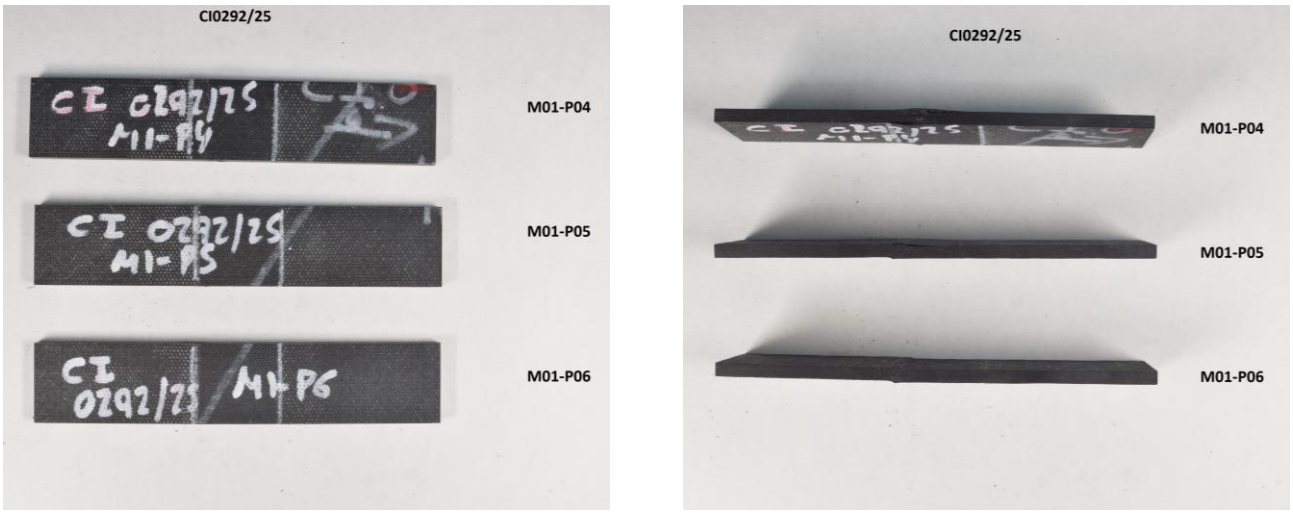

Figure 4. Failure mode of coupons tested at 50°C without tabs. Up: Tensile test. Down: Compression test.

5. TEST CAMPAIGN

5.1 TEST PLAN DEFINITION

According to D6.1, the mechanical test campaign to be performed to coupons in INFINITE project is shown in Table 3. Some of the standards have been changed with respect to D6.1, as shown in the following table.

Test	Standard	Standard in D6.1
Interlaminar shear strength	UNE-EN 2563	EN 2563
Flexure	ASTM D790	ASTM D790
In plane shear strength	ASTM D3518/D3518M	AITM 1-0002
Tensile test, plain coupon	AITM 1-0007	ISO 527-4
Tensile test, open hole coupon	AITM 1-0007	AITM 1-0007
Tensile test, filled hole coupon	AITM 1-0007	AITM 1-0007
Compression test, plain coupon	AITM 1-0008	AITM 1-0008
Compression test, open hole coupon	AITM 1-0008	AITM 1-0008
Compression test, filled hole coupon	AITM 1-0008	AITM 1-0008

Table 3. Mechanical tests performed in INFINITE project, with applicable standards.

These tests have been performed to reference coupons (without microwires) and to sensorised coupons (with microwires). Both conditions have been always tested under the same testing parameters.

Generally, the execution of these mechanical tests requires the use of some dispositive that enables the measurement of the deformation of the tested coupons. The most used options are strain gauges and extensometer. The use of microwires which are activated with magnetic field presents a risk of interference with the signals read with strain gauges. Because of this reason, the use of a Digital Image Correlation (DIC) equipment has been used in this project as an alternative to traditional methods. Before its use on the test campaign, the results obtained with this equipment were validated by comparison with results obtained with strain gauges, Figure 6. In this figure, it can be observed the measurements of micro strain performed registered with strain gauges and with DIC. It can be observed that both lines present similar values and behaviour.

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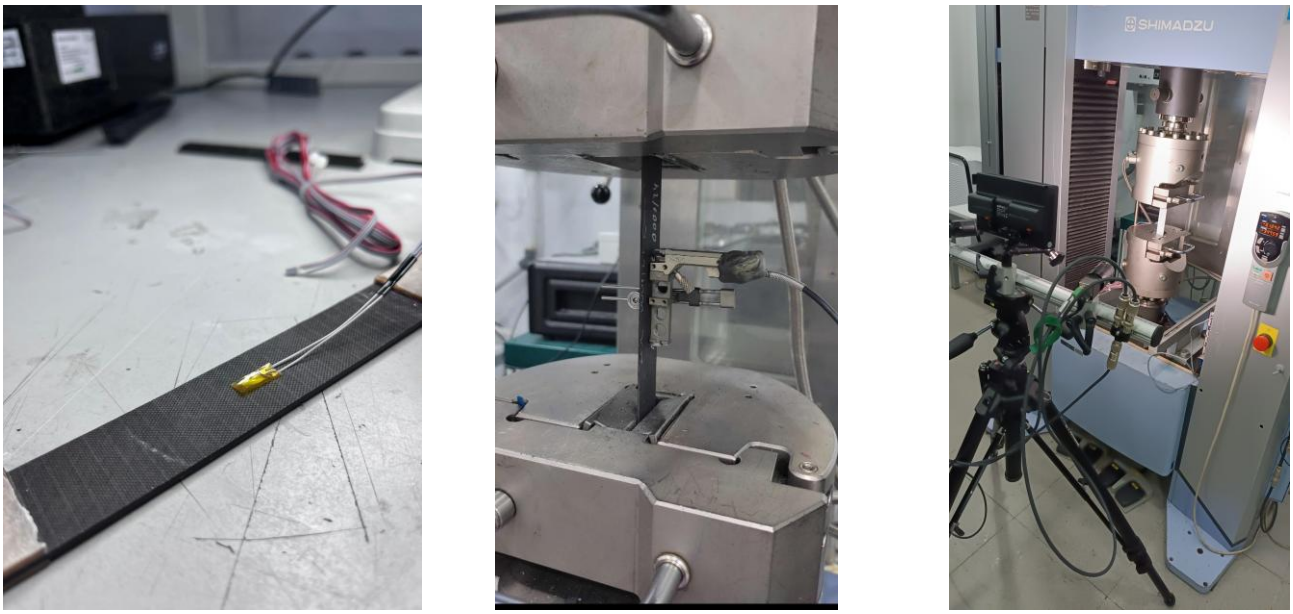

Figure 5. Left: Strain gauge. Centre: Extensometer. Right: DIC

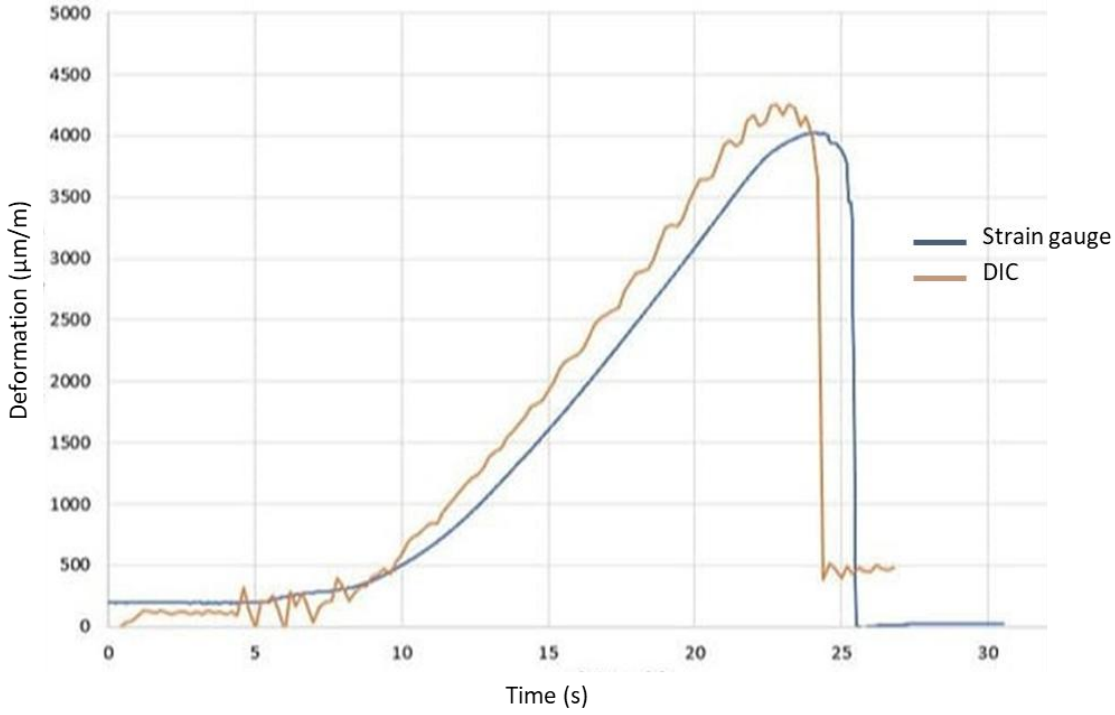

Figure 6. Deformation registered by DIC and strain gauges during a mechanical test.

Thus, different techniques for the measurement of deformations have been used in this project:

- Reference coupons: Strain gauges, DIC and extensometer
- Sensorised coupons, ambient conditions: DIC and extensometer
- Sensorised coupons, not ambient conditions: Extensometer

Regarding to testing machines, different universal testing machines have been used. The main difference among them was the load cell used (10, 100 and 250 kN). Regarding to clamps, for tensile tests and in-plane shear tests,

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self-aligning hydraulic clamps have been used. With regard to compression test, hydraulic composites compression fixture (HCCF) clamps have been used.

5.2 TEST DESCRIPTION

5.2.1 INTERLAMINAR SHEAR STRENGTH TEST

Interlaminar shear strength tests have been performed according to UNE-EN 2563 standard. The lay-up defined to this test was [(0°/90°),(90°/0°)]s. Figure 7 shows the geometry and dimensions of this type of test coupon. For each test panel, five coupons are obtained and tested.

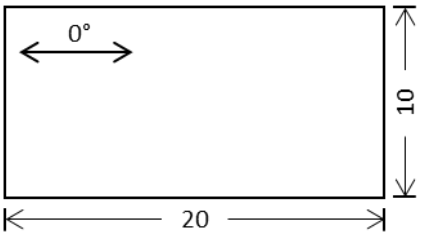

Figure 7. Coupon geometry for interlaminar shear strength test, according to UNE-EN 2563. All dimensions are expressed in mm.

A critical parameter in this type of tests is the span distance. This is the separation between the support points of the coupon in the set-up of the universal testing machine. Since this test campaign aims to compare the behaviour of panels with and without microwires, it was decided to establish this span distance in 10 mm for all tested coupons.

Figure 8. Detail of span in a lap shear strength test.

5.2.2 FLEXURE TEST

Flexural tests have been performed according to ASTM D790 standard. The lay-up defined for this test was [(+45°/-45°),(-45°/+45°)]s. Figure 9 shows the geometry and dimensions of this type of test coupon. For each test panel, five coupons are obtained and tested.

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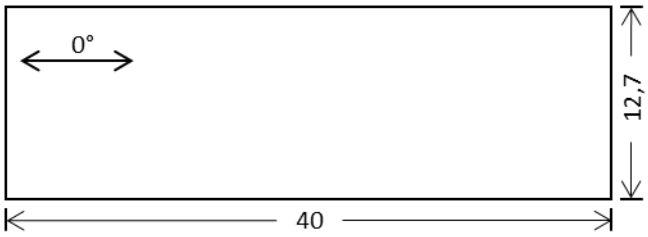

Figure 9. Coupon geometry for flexure test, according to ASTM D790. All dimensions are expressed in mm.

5.2.3 IN-PLANE SHEAR TEST

In-plane shear tests have been performed according to ASTM D3518/D3518M. The lay-up defined for this test was [(+45°/-45°),(-45°/+45°)]2s. According to this standard, the use of tabs depends on the thickness of the laminate. Since the laminates are thick enough, tabs are not required. Figure 10 shows the geometry of this type of test coupons. For each test panel, five coupons are obtained and tested. Considering the clamping distance, the free area to be tested is 230 x 25mm.

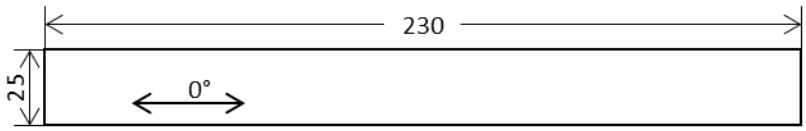

Figure 10. Coupon geometry for in-plane shear test, according to ASTM D3518/D3518M. All dimensions are expressed in mm.

According to the standard, the test velocity shall be defined as a function of time test. Thus, the test should last between 1 and 10 minutes. According to TITANIA's internal procedures, the initial testing speed is 5 mm/min. If this velocity complies with the requirement of time, it is stablished as the testing velocity.

5.2.4 TENSILE TEST

Tensile tests have been performed according to AITM 1-0007, for all tested configurations (plain, open hole (OHT) and filled hole (FHT)). The lay-up defined for this test was [(+45°/-45°),(90°/0°)]3s.
As commented in previous sections of this deliverable, some tests were performed to define whether tabs shall be used or not. It was confirmed that the use of tabs was required for plain coupons, but not for open hole and filled hole ones. On the other hand, the standard defines the dimensions of the coupons as a function of the thickness. Thus, the coupons have dimensions of 250 (0°) x 22 mm, with clamping distance (and tabs when required) of 50 mm.

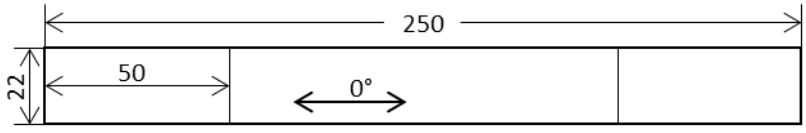

Figure 11. Coupon geometry for tensile test - plain coupon, according to AITM1-0007. All dimensions are expressed in mm.

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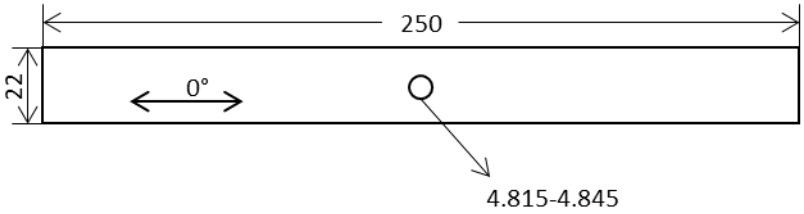

Figure 12. Coupon geometry for tensile test - OHT coupon, according to AITM1-0007. All dimensions are expressed in mm.

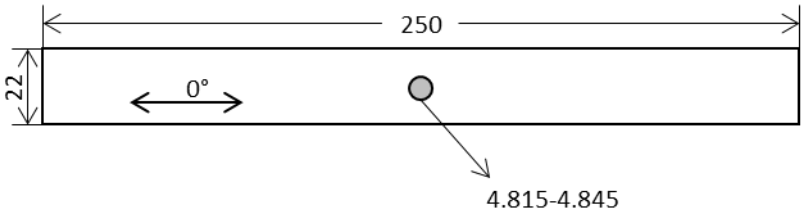

Figure 13. Coupon geometry for tensile test - FHT coupon, according to AITM1-0007. All dimensions are expressed in mm.

For filled hole coupons, aeronautical rivets and nuts were used, ABS0114T4-3 and NAS1726-4E, respectively.

5.2.5 COMPRESSION TEST

Compression tests have been performed according to AITM 1-0008, for all tested configurations (plain, open hole (OHT) and filled hole (FHT)). The lay-up defined for this test was [(+45°/-45°),(90°/0°)]3s.
The standard defines the dimensions of the coupons as a function of the thickness. Thus, the coupons have dimensions of 152 (0°) x 22 mm, with clamping distance (and tabs when required) of 65 mm.

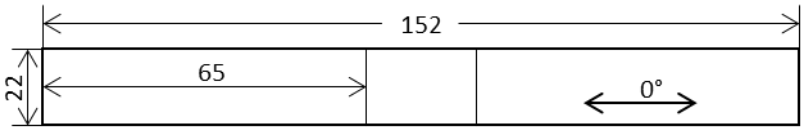

Figure 14. Coupon geometry for compression test - plain coupon, according to AITM1-0008. All dimensions are expressed in mm.

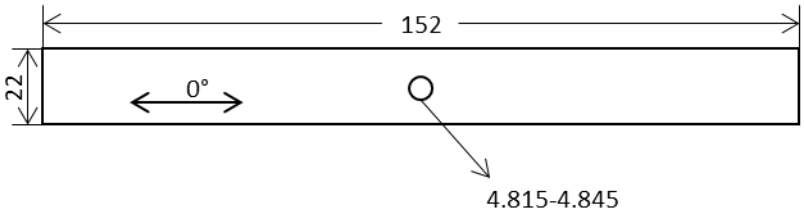

Figure 15. Coupon geometry for compression test - OHC coupon, according to AITM1-0008. All dimensions are expressed in mm.

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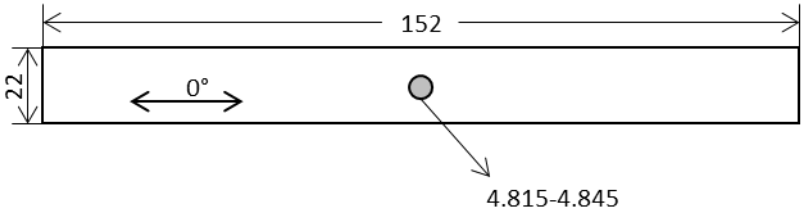

Figure 16. Coupon geometry for compression test - FHC coupon, according to AITM1-0008. All dimensions are expressed in mm.

For filled hole coupons, aeronautical rivets and nuts were used, ABS0114T4-3 and NAS1726-4E, respectively.

5.3 TESTING CONDITIONS

Different testing conditions have been established to perform the most extensive analysis. Thus, the test campaign has been performed at:

- Room temperature (RT)

Coupons are tested as received, at room temperature. No previous conditioning is required.

- High temperature (HT)

Initially, high temperature tests were planned to be performed at 90°C. However, due to the low Tg temperature of the resin system (64°C), testing at this temperature may cause damage to the material and decrease mechanical properties. Because of this reason, the testing temperature was set at 50°C. The difference of 14°C between Tg and testing temperature was considered enough as not to have doubts on possible the nature of changes on mechanical properties. With this difference on temperature, changes would be related to testing temperature, and not to changes derived from proximity to Tg.

To obtain the desired temperature, a temperature chamber is adapted to the universal testing machine, and temperature is controlled with calibrated thermocouples.

Figure 17. Set-up for high temperature testing.

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- Low temperature (LT)

Coupons are tested at -55°C. This time, the temperature is obtained by using the same temperature chamber, but using liquid nitrogen to descend the temperature. Again, the temperature is controlled with calibrated thermocouples.

Figure 18. Set-up for low temperature testing

- WET conditioning

WET condition implies ageing of coupons in a climatic chamber under controlled conditions. One of the most common conditions is 70°C and 85% RH. However, it is not possible to use these conditions because of the Tg value. This way, the temperature used for conditioning process was 50°C, whilst the RH was maintained at 85%. This ageing conditioning implies keeping the coupons in climatic chamber until weight equilibrium is obtained and maintained for three weeks. The control is performed by weight changes, performed to travellers coupons. Figure 19 shows an example of the weight evolution of a traveller coupon until equilibrium. Initially, this condition was defined as WET and high temperature. However, it was decided to change it to RT/WET because of the value of Tg. These tests were the last on be performed, so that results of high temperature tests were known. The obtained results under high temperature reinforced the decision of performing WET tests at RT.

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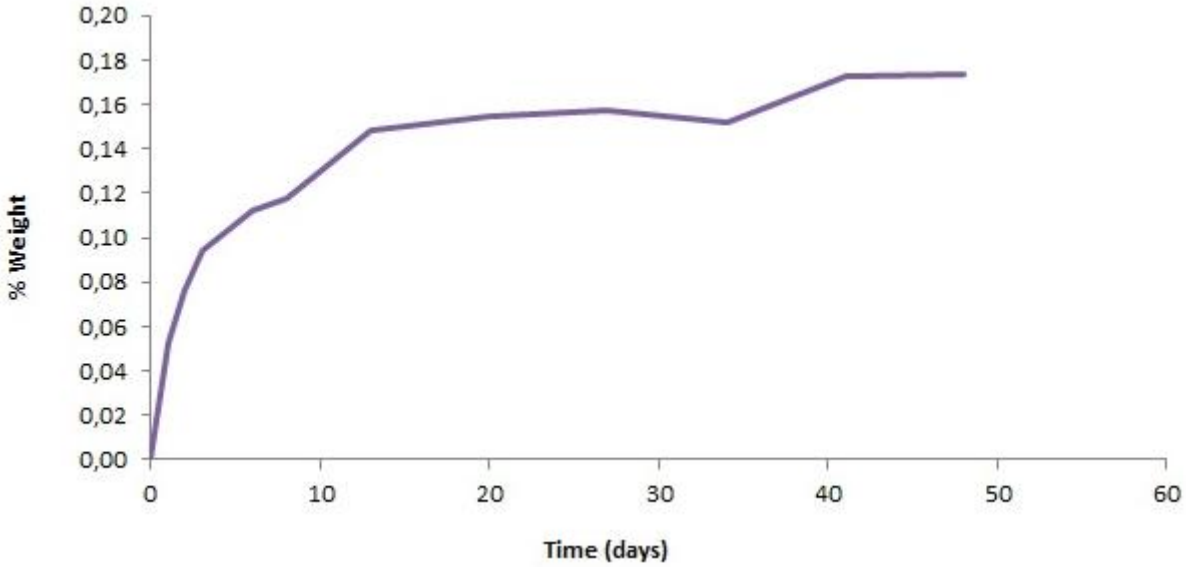

Figure 19. Weight control graph of a traveller for WET testing condition.

Non ambient and ageing conditions have a requirement of stabilizing time. Generally, it implies that the coupon shall be 5 minutes at the testing temperature before starting the test. In case of WET condition, coupons shall be tested withing the first 4 hours after being out of the climatic chamber.

The number of batches tested changes depending on the testing condition and the type of coupon. Table 4 shows the number of batches defined for this test campaign.

Condition	RT	High temperature	Low temperature	WET
Reference (No MW)	3	1	1	1
Sensorised (MW)	5	3	3	3

Table 4. Number of batches tested for different conditions.

6. TEST RESULTS

Following are presented the results obtained for the performed tests campaign. Annex I includes the failure mode photography of tested coupons.

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6.1 REFERENCE COUPONS

	Short beam strength (MPa)			
	RT	High temperature	Low temperature	WET
Batch 1	41.6 ± 2.6	6.3 ± 0.5	68.2 ± 4.0	38.8 ± 1.0
Batch 2	41.1 ± 1.4	-	-	-
Batch 3	40.8 ± 2.2	-	-	-
Mean	**41.2 ± 0.4**	**6.3 ± 0.5**	**68.2 ± 4.0**	**38.8 ± 1.0**

Table 5. Results for interlaminar shear strength tests performed for reference coupons (No MW).

	Flexural strength (MPa)				Modulus in bending (GPa)			
	RT	HT	LT	WET	RT	HT	LT	WET
Batch 1	316 ± 8	N.P.	N.P.	N.P.	11134 ± 559	N.P.	N.P.	N.P.
Batch 2	320 ± 18				11507 ± 1092			
Batch 3	298 ± 13				10363 ± 351			
Mean	**311 ± 12**				**11001 ± 583**			

Table 6. Results for flexure tests performed for reference coupons (No MW)

Flexure tests have not been performed at non ambient conditions since the clamps required for this test are not adapted for temperature chamber.

	Shear strength (MPa)				Shear modulus (GPa)			
	RT	HT	LT	WET	RT	HT	LT	WET
Batch1	48.9 ± 0.6	7.4 ± 0.5	85.8 ± 1.9	38.3 ± 0.2	3.66 ± 0.15	0.18 ± 0.02	4.87 ± 0.33	2.75 ± 0.05
Batch2	44.3 ± 1.4	-	-	-	3.35 ± 0.12	-	-	-
Batch3	49.5 ± 3.4	-	-	-	3.65 ± 0.14	-	-	-
Mean	**47.6 ± 2.8**	**7.4 ± 0.5**	**85.8 ± 1.9**	**38.3 ± 0.2**	**3.55 ± 0.18**	**0.18 ± 0.02**	**4.87 ± 0.33**	**2.75 ± 0.05**

Table 7. Results for in-plane shear tests performed for reference coupons (No MW)

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	Tensile strength (MPa)				Modulus of elasticity (GPa)			
	RT	HT	LT	WET	RT	HT	LT	WET
Batch 1	716.1 ± 39.5	N.P.	770.2 ± 26.4	730.0 ± 15.4	47.4	N.P.	49.4 ± 1.0	45.0 ± 0.5
Batch 2	741.3 ± 27.6		-	-	47.2		-	-
Batch 3	735.8 ± 24.5		-	-	47.4		-	-
Mean	**731.1 ± 13.3**		**770.2 ± 26.4**	**730.0 ± 15.4**	**47.3 ± 0.1**		**49.4 ± 1.0**	**45.0 ± 0.5**

Table 8. Results for tensile tests, plain coupons, performed for reference coupons (No MW).

	Tensile strength (MPa)			
	RT	HT	LT	WET
Batch 1	412 ± 12.6	384.0 ± 5.2	446.0 ± 9.1	404.6 ± 10.9
Batch 2	415.2 ± 5.9	-	-	-
Batch 3	414.1 ± 13.3	-	-	-
Mean	**413.8 ± 1.6**	**384.0 ± 5.2**	**446.0 ± 9.1**	**404.6 ± 10.9**

Table 9. Results for tensile tests, OHT coupons, performed for reference coupons (No MW).

	Tensile strength (MPa)			
	RT	HT	LT	WET
Batch 1	397.7 ± 8.7	353.3 ± 5.2	452.0 ± 16.9	387.6 ± 9.7
Batch 2	406.5 ± 10.6	-	-	-
Batch 3	404.9 ± 9.6	-	-	-
Mean	**403.3 ± 4.7**	**353.3 ± 5.2**	**452.0 ± 16.9**	**387.6 ± 9.7**

Table 10. Results for tensile tests, FHT coupons, performed for reference coupons (No MW).

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

	Tensile strength (MPa)				Compression secant modulus (GPa)			
	RT	HT	LT	WET	RT	HT	LT	WET
Batch 1	430.7 ± 15.8	N.P.	513.3 ± 47.7	406.5 ± 24.4	44.9 ± 2.6	N.P.	44.3 ± 1.7	42.9 ± 1.3
Batch 2	459.0 ± 20.2		-	-	45.8 ± 2.2			
Batch 3	468.7 ± 18.9		-	-	42.9 ± 2.0			
Mean	**452.8 ± 19.7**		**513.3 ± 47.7**	**406.5 ± 24.4**	**44.5 ± 1.5**		**44.3 ± 1.7**	**42.9 ± 1.3**

Table 11. Results for compression tests, plain coupons, performed for reference coupons (No MW).

	Compression strength (MPa)			
	RT	HT	LT	WET
Batch 1	241.0 ± 8.9	50.7 ± 15.9	343.0 ± 14.6	446.0 ± 9.1
Batch 2	235.0 ± 7.6	-	-	-
Batch 3	224.0 ± 9.3	-	-	-
Mean	**233.3 ± 8.6**	**50.7 ± 15.9**	**343.0 ± 14.6**	**446.0 ± 9.1**

Table 12. Results for compression tests, OHC coupons, performed for reference coupons (No MW).

	Tensile strength (MPa)			
	RT	HT	LT	WET
Batch 1	369.7 ± 8.2	101.9 ± 36.6	520.6 ± 14.8	452.0 ± 16.9
Batch 2	368.3 ± 9.9	-	-	-
Batch 3	358.1 ± 11.4	-	-	-
Mean	**365.4 ± 6.3**	**101.9 ± 36.6**	**520.6 ± 14.8**	**452.0 ± 16.9**

Table 13. Results for compression tests, FHC coupons, performed for reference coupons (No MW).

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6.2 SENSORISED COUPONS

	Short beam strength (MPa)			
	RT	High temperature	Low temperature	WET
Batch 1	44.5 ± 2.0	6.7 ± 0.3	66.2 ± 2.4	38.5 ± 0.2
Batch 2	40.4 ± 1.0	7.2 ± 0.2	62.5 ± 7.5	39.9 ± 2.2
Batch 3	44.6 ± 1.2	6.4 ± 0.2	63.1 ± 5.3	36.8 ± 1.4
Batch 4	42.8 ± 1.6	-	-	-
Batch 5	42.6 ± 0.7	-	-	-
Mean	**43.0 ± 1.7**	**6.8 ± 0.4**	**63.9 ± 2.0**	**38.4 ± 1.6**

Table 14. Results for interlaminar shear strength tests performed for sensorised coupons (MW).

	Flexural strength (MPa)				Modulus in bending (GPa)			
	RT	HT	LT	WET	RT	HT	LT	WET
Batch 1	300 ± 12	N.P.	N.P.	N.P.	13272 ± 764	N.P.	N.P.	N.P.
Batch 2	305 ± 15				13460 ± 516			
Batch 3	300 ± 15				12684 ± 891			
Batch 4	305 ± 4				13949 ± 415			
Batch 5	294 ± 9				12622 ± 1613			
Mean	**301 ± 5**				**13197 ± 555**			

Table 15. Results for flexure tests performed for sensorised coupons (MW)

Flexure tests have not been performed at non ambient conditions since the clamps required for this test are not adapted for temperature chamber.

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	Shear strength (MPa)				Shear modulus (GPa)			
	RT	HT	LT	WET	RT	HT	LT	WET
Batch 1	46.6 ± 4.3	10.3 ± 0.8	92.1 ± 4.9	36.9 ± 0.7	3.71 ± 0.84	0.21 ± 0.03	4.55 ± 0.26	2.71 ± 0.05
Batch 2	46.4 ± 5.9	8.0 ± 0.3	89.4 ± 6.3	37.0 ± 0.9	3.20 ± 0.47	0.19 ± 0.03	4.33 ± 0.04	2.79 ± 0.16
Batch 3	46.6 ± 5.0	9.3 ± 2.1	88.5 ± 1.8	37.1 ± 0.7	2.63 ± 0.37	0.30 ± 0.22	4.80 ± 0.43	2.77 ± 0.13
Batch 4	41.4 ± 1.1	-	-		2.95 ± 0.22	-	-	-
Batch 5	43.6 ± 1.9	-	-		2.86 ± 0.53	-	-	-
Mean	**44.9 ± 2.3**	**9.2 ± 1.2**	**90.0 ± 1.9**	**37.0 ± 0.1**	**3.07 ± 0.41**	**0.23 ± 0.06**	**4.56 ± 0.24**	**2.76 ± 0.04**

Table 16. Results for in-plane shear tests performed for sensorised coupons (MW)

	Tensile strength (MPa)				Modulus of elasticity (GPa)			
	RT	HT	LT	WET	RT	HT	LT	WET
Batch 1	672.3 ± 50.5		699.2 ± 31.2	617.7 ± 64.8	45.1 ± 0.7		46.3 ± 0.8	42.2 ± 0.4
Batch 2	693.1 ± 27.6		711.1 ± 37.0	664.0 ± 8.1	44.9 ± 0.7		46.9 ± 1.5	41.6 ± 0.7
Batch 3	671.8 ± 27.2	N.P.	734.8 ± 25.9	586.7 ± 24.0	43.4 ± 1.1	N.P.	46.8 ± 0.1	43.0 ± 0.1
Batch 4	642.6 ± 39.0		-	-	43.3 ± 0.6		-	-
Batch 5	674.9 ± 33.0		-	-	42.8 ± 0.8		-	-
Mean	**670.9 ± 18.1**		**715.0 ± 18.1**	**622.8 ± 38.8**	**43.9 ± 1.0**		**46.7 ± 0.3**	**42.3 ± 0.7**

Table 17. Results for tensile tests, plain coupons, performed for sensorised coupons (MW).

	Tensile strength (MPa)			
	RT	HT	LT	WET
Batch 1	410.3 ± 4.8	389.1 ± 12.0	411.4 ± 20.6	395.2 ± 12.6
Batch 2	404.4 ± 8.7	398.9 ± 9.4	379.0 ± 10.2	408.0 ± 14.6
Batch 3	404.3 ± 14.5	396.7 ± 8.6	385.9 ± 14.1	366.6 ± 2.0
Batch 4	403.9 ± 6.2	-	-	-
Batch 5	400.1 ± 7.5	-	-	-
Mean	**404.6 ± 3.7**	**394.9 ± 5.1**	**392.1 ± 17.1**	**389.9 ± 21.2**

Table 18. Results for tensile tests, OHT coupons, performed for sensorised coupons (MW).

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	Tensile strength (MPa)			
	RT	HT	LT	WET
Batch 1	395.5 ± 6.4	360.4 ± 5.2	392.4 ± 9.1	371.6 ± 3.6
Batch 2	389.1 ± 8.3	359.1 ± 5.5	384.3 ± 9.7	374.2 ± 11.1
Batch 3	401.6 ± 11.9	360.0 ± 4.7	371.2 ± 13.5	339.1 ± 5.1
Batch 4	397.5 ± 8.8	-	-	-
Batch 5	386.4 ± 10.3	-	-	-
Mean	**394.0 ± 6.2**	**359.8 ± 0.7**	**382.6 ± 10.7**	**361.6 ± 19.6**

Table 19. Results for tensile tests, FHT coupons, performed for sensorised coupons (MW).

	Compression strength (MPa)				Compression secant modulus (GPa)			
	RT	HT	LT	WET	RT	HT	LT	WET
Batch 1	417.5 ± 10.7	N.P.	619.0 ± 28.4	367.0 ± 9.7	40.2 ± 1.9	N.P.	39.4 ± 2.2	39.4 ± 0.4
Batch 2	402.0 ± 32.7		559.3 ± 50.1	329.9 ± 13.8	41.3 ± 1.4		41.1 ± 0.3	40.3 ± 0.7
Batch 3	367.9 ± 19.9		532.9 ± 46.0	331.6 ± 26.2	39.4 ± 2.5		40.6 ± 0.8	38.5 ± 0.9
Batch 4	361.7 ± 14.8		-	-	38.9 ± 3.5		-	-
Batch 5	390.9 ± 10.0		-	-	39.6 ± 2.2		-	-
Mean	**388.0 ± 23.3**		**570.4 ± 44.1**	**342.8 ± 20.9**	**39.9 + 0.9**		**40.4 ± 0.9**	**39.4 ± 0.9**

Table 20. Results for compression tests, plain coupons, performed for sensorised coupons (MW).

	Compression strength (MPa)			
	RT	HT	LT	WET
Batch 1	210.2 ± 10.2	173.0 ± 2.2	327.8 ± 22.4	223.4 ± 4.5
Batch 2	210.4 ± 5.7	175.5 ± 4.2	280.7 ± 4.1	217.9 ± 12.2
Batch 3	206.3 ± 4.8	172.4 ± 6.2	274.6 ± 5.1	190.7 ± 14.3
Batch 4	212.9 ± 8.1	-	-	-
Batch 5	215.5 ± 5.0	-	-	-
Mean	**211.1 ± 3.4**	**173.6 ± 1.6**	**294.4 ± 29.1**	**210.7 ± 17.5**

Table 21. Results for compression tests, OHC coupons, performed for sensorised coupons (MW).

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	Compression strength (MPa)			
	RT	HT	LT	WET
Batch 1	324.2 ± 11.8	274.1 ± 10.7	504.4 ± 12.7	349.8 ± 1.4
Batch 2	320.9 ± 6.3	273.2 ± 12.1	440.1 ± 21.0	351.4 ± 2.1
Batch 3	316.2 ± 8.9	266.2 ± 9.2	435.6 ± 14.8	277.0 ± 13.5
Batch 4	326.0 ± 11.2	-	-	-
Batch 5	327.7 ± 10.8	-	-	-
Mean	**322.0 ± 3.7**	**271.2 ± 4.3**	**460.0 ± 38.5**	**326.1 ± 42.5**

Table 22. Results for compression tests, FHC coupons, performed for sensorised coupons (MW).

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6.3 COMPARATIVE GRAPHS

This section includes bar graphs in which the behaviour of each studied mechanical property is represented. Each graph shows the mean value of all testing conditions for both studied conditions, reference (no microwires) and sensorised (with microwires).

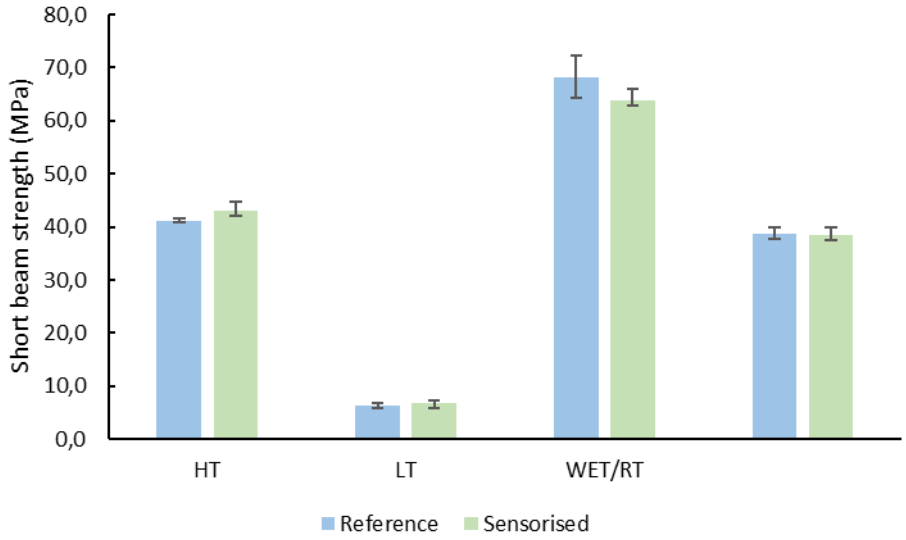

Figure 20. Changes on short beam strength measured in interlaminar shear strength test for all testing conditions. Blue: non sensorised coupons. Green: coupons sensorised with microwires.

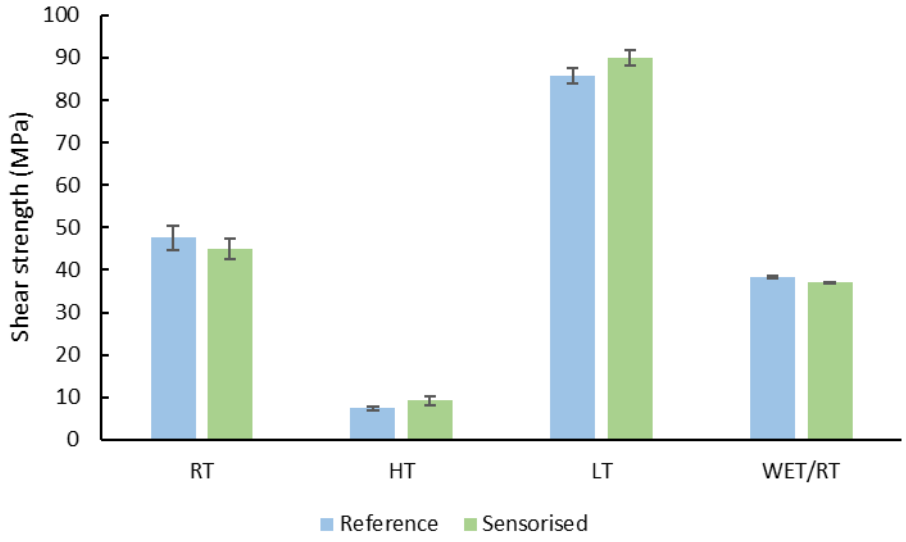

Figure 21. Changes on shear strength measured in in-plane shear strength test for all testing conditions. Blue: non sensorised coupons. Green: coupons sensorised with microwires.

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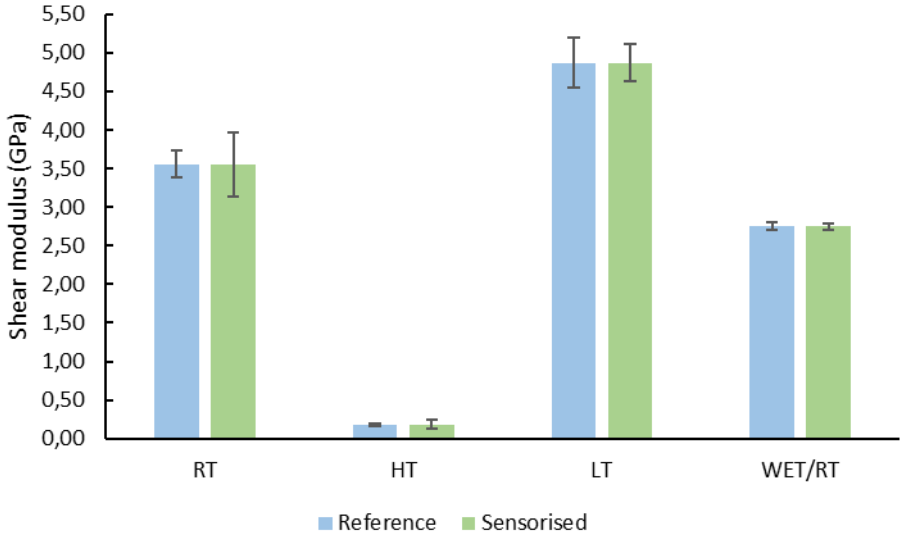

Figure 22. Changes on shear modulus measured in in-plane shear strength test for all testing conditions. Blue: non sensorised coupons. Green: coupons sensorised with microwires.

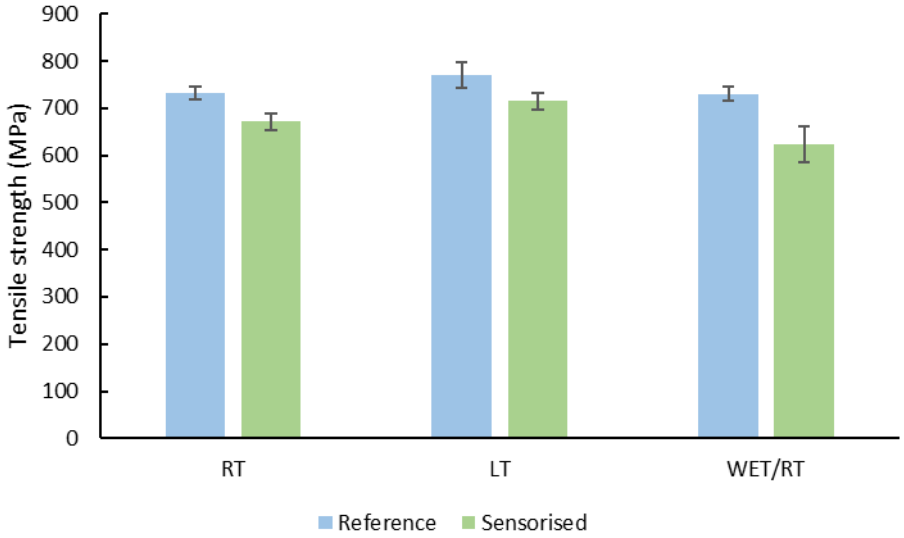

Figure 23. Changes on tensile strength measured in tensile test (plain coupons) for all testing conditions. Blue: non sensorised coupons. Green: coupons sensorised with microwires.

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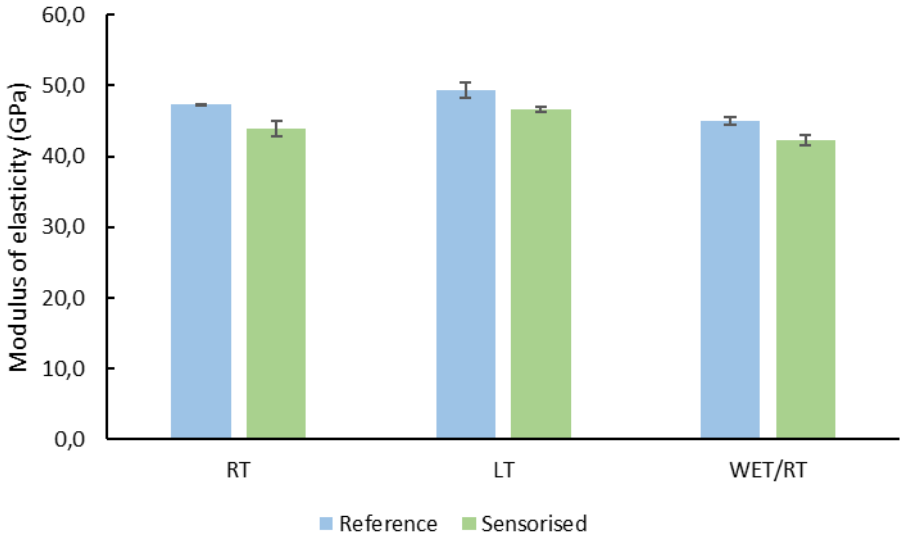

Figure 24. Changes on modulus of elasticity measured in tensile test (plain coupons) for all testing conditions. Blue: non sensorised coupons. Green: coupons sensorised with microwires.

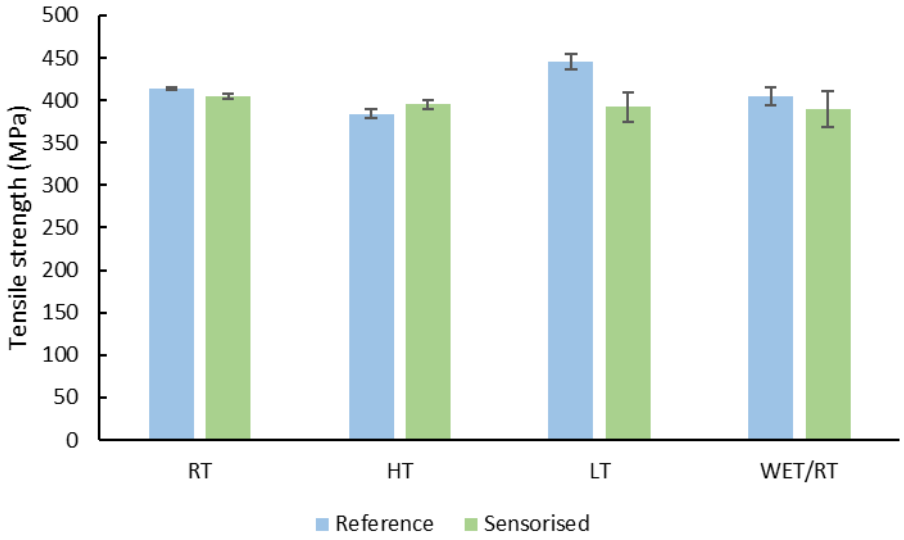

Figure 25. Changes on tensile strength measured in tensile test (OHT coupons) for all testing conditions. Blue: non sensorised coupons. Green: coupons sensorised with microwires.

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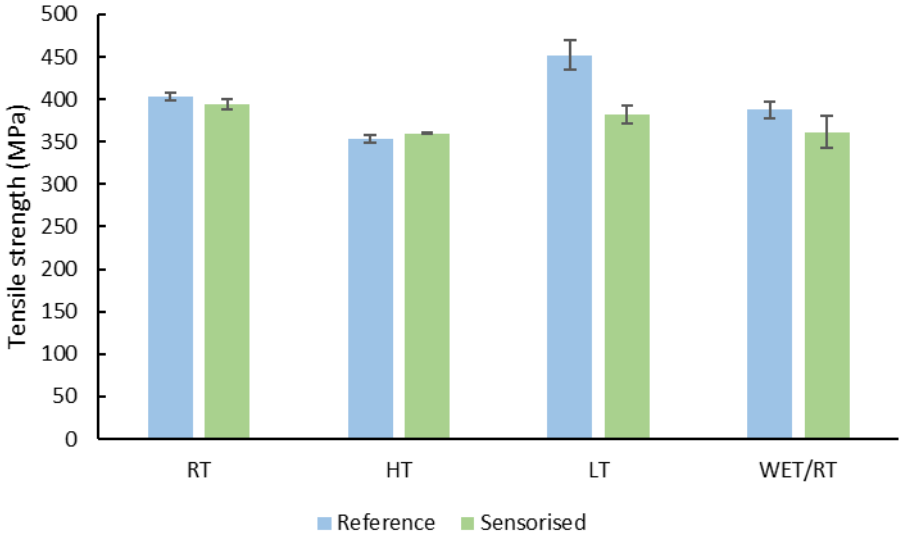

Figure 26. Changes on tensile strength measured in tensile test (FHT coupons) for all testing conditions. Blue: non sensorised coupons. Green: coupons sensorised with microwires.

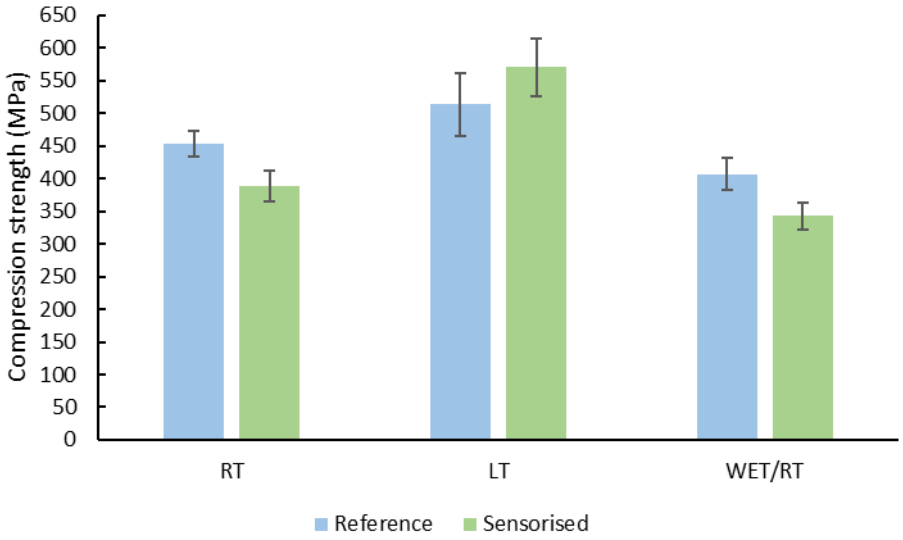

Figure 27. Changes on compression strength measured in compression test (plain coupons) for all testing conditions. Blue: non sensorised coupons. Green: coupons sensorised with microwires.

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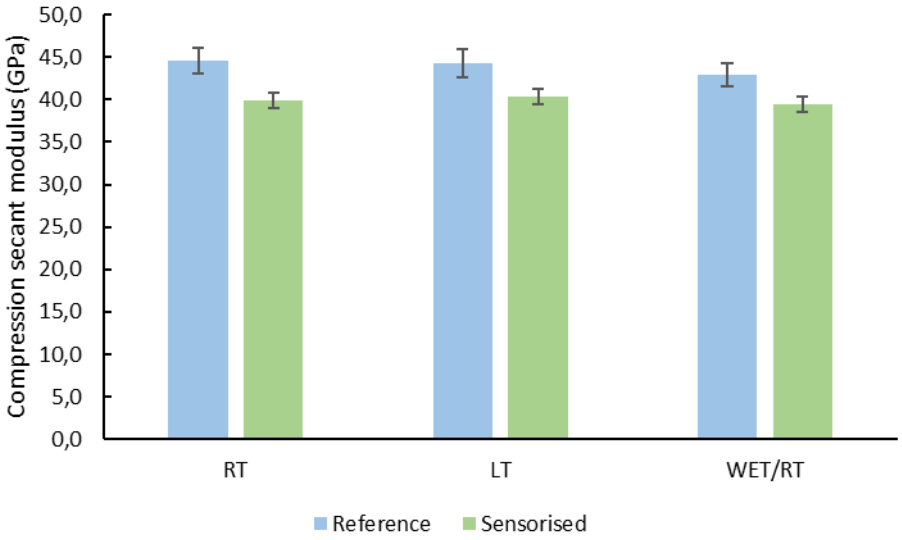

Figure 28. Changes on compression secant modulus measured in compression test (plain coupons) for all testing conditions. Blue: non sensorised coupons. Green: coupons sensorised with microwires.

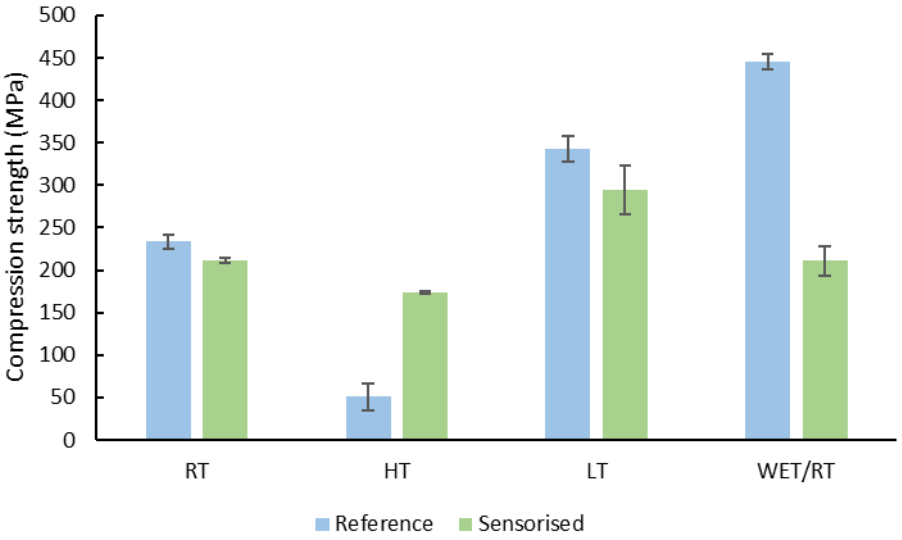

Figure 29. Changes on compression strength measured in compression test (OHC coupons) for all testing conditions. Blue: non sensorised coupons. Green: coupons sensorised with microwires.

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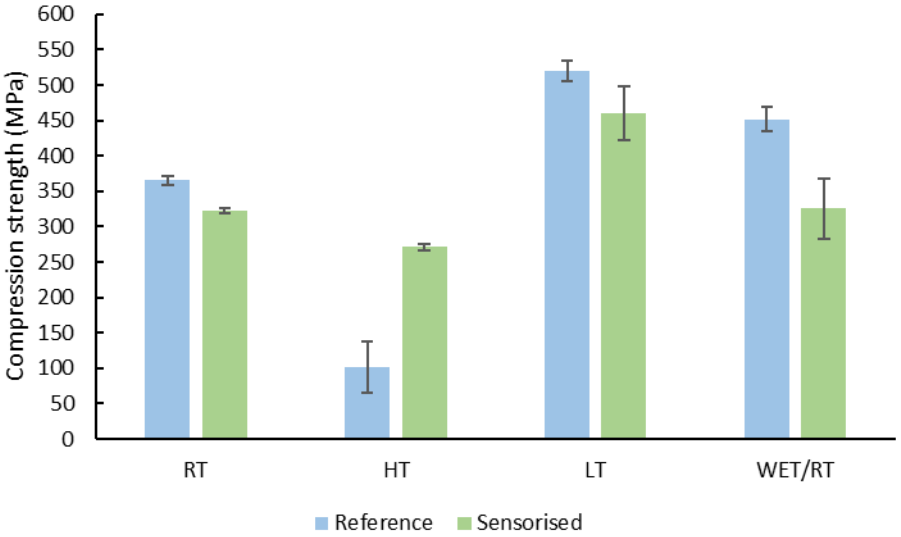

Figure 30. Changes on compression strength measured in compression test (FHC coupons) for all testing conditions. Blue: non sensorised coupons. Green: coupons sensorised with microwires.

The analysis of these graphs shows that, in general lines, the studied NCF/resin system studied in the project present bad behaviour at high temperature. This can be related with the non-aeronautical grade of the used resin. The low value of Tg indicates that this resin is thought to be used at ambient conditions. Furthermore, it has been also observed that coupons present great mechanical properties when testing at low temperature (-55°). In case of aged coupons, the behaviour is similar to this observed for non-aged coupons, so that a negative effect of humidity absorption could be discarded.

7. ANALYSIS OF RESULTS

Table 23 includes an evaluation of the variation of mechanical properties for non sensorised coupons, considered as reference, and sensorised coupons with microwires. The aim of this analysis is to determine the possible effect that the inclusion on microwires may have on the properties of the laminates. Thus, differences higher than 10% between both conditions have been considered as relevant.

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Property	No MW	RT MW	Variation	No MW	HT MW	Variation	No MW	LT MW	Variation	No MW	WET MW	Variation
Short beam strength (MPa)	41.2	43.0	+4%	6.3	6.8	+7%	68.2	63.9	-6%	38.8	38.4	-1%
Flexural strength (MPa)	311	301	-3%		-			-			-	
Modulus in bending (MPa)	11001	13197	+20%		-			-			-	
Shear strength (MPa)	47.6	44.9	-6%	7.4	9.2	+24%	85.8	90.0	+5%	38.3	37.0	-3%
Shear modulus (GPa)	3.55	3.07	-14%	0.18	0.23	+30%	4.87	4.56	-6%	2.75	2.76	0%
Tensile strength (MPa)	731.1	670.9	-8%		-		770.2	715.0	-7%	730.0	622.8	-15%
Modulus of elasticity (GPa)	47.3	43.9	-7%		-		49.4	46.7	-6%	45.0	42.3	-6%
Tensile strength, OHT (MPa)	413.8	404.6	-2%	384.0	394.9	+3%	446.0	392.1	-12%	404.6	389.9	-4%
Tensile strength, FHT (MPa)	403.0	394.0	-2%	353.3	359.8	+2%	452.0	382.6	-15%	387.6	361.6	-7%
Compression strength (MPa)	452.8	388.0	-14%		-		513.3	570.4	+11%	406.5	342.8	-16%

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Compression secant modulus (GPa)	44.5	39.9	-10%				44.3	40.4	-9%	42.9	39.4	-8%
Compression strength, OHC (MPa)	233.3	211.1	-10%	50.7	173.6	+242%	343.0	294.4	-14%	446.0	210.7	-53%
Compression strength, FHC (MPa)	365.4	322.0	-12%	101.9	271.2	+166%	520.6	460.0	-12%	452.0	326.1	-28%

Table 23. Analysis of the changes on mechanical properties between non sesonrised and sensorised with MW coupons at different testing conditions

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Table 24 summarises the properties which have shown remarkable variation between the non sensorised and the sensorised with microwires coupons. Variation is referred to sensorised coupons, so that increase means that these coupons presented higher values than non sensorised ones, whilst decrease implies lower values. This table does not include properties which presented variations higher than 30%. These great variations have been related to deviations during mechanical tests.

Property	Testing condition	Variation
Modulus in bending	RT	Increase
Shear strength	HT	Increase
Shear modulus	RT	Decrease
Shear modulus	HT	Increase
Tensile strength, plain	WET/RT	Decrease
Tensile strength, OHT	LT	Decrease
Tensile strength, FHT	LT	Decrease
Compression strength, plain	RT	Decrease
Compression strength, plain	LT	Increase
Compression strength, plain	WET/RT	Decrease
Compression strength, OHC	LT	Decrease
Compression strength, FHC	RT	Decrease
Compression strength, FHC	LT	Decrease
Compression strength, FHC	WET/RT	Decrease

Table 24. Summary of remarkable variations on mechanical properties between non sensorised and sensorised with microwires coupons.

8. CONCLUSIONS

Results obtained in this report have led to the following conclusions:

- A test campaign has been performed to analyse the influence of inclusion of microwires on NCF laminates. Thus, reference coupons (non sensorised) and sensorised with microwires coupons have been tested.
- The use of a resin system with low Tg temperature have implied some difficulties related to high temperature testing and use of tabbing. Relative low temperature (50°C) has been set for high temperature testing conditions. On the other hand, it has been impossible to find an adhesive which present high loads for high temperature and low curing temperature. As a consequence of this, tensile and compression tests at high temperature could not be performed.
- Remarkable differences between both conditions have been found for test performed at low temperature. At -55°C, coupons with microwires presented lower properties than non sensorised coupons. These variations are related, mainly, with compression strength values.
- The fact that remarkable variations have been identified for non-ambient testing conditions, and not at RT, suggests that these variations are due to the used resin system and not to the inclusion of microwires.
- In case of positive results obtained with portable reader lectures, it would be recommended to perform a reduced test campaign with an aeronautical resin system, in order to prove that that variations are related to resin and not to the addition of microwires in the structure.

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9. ANNEX I. FAILURE MODE IMAGES

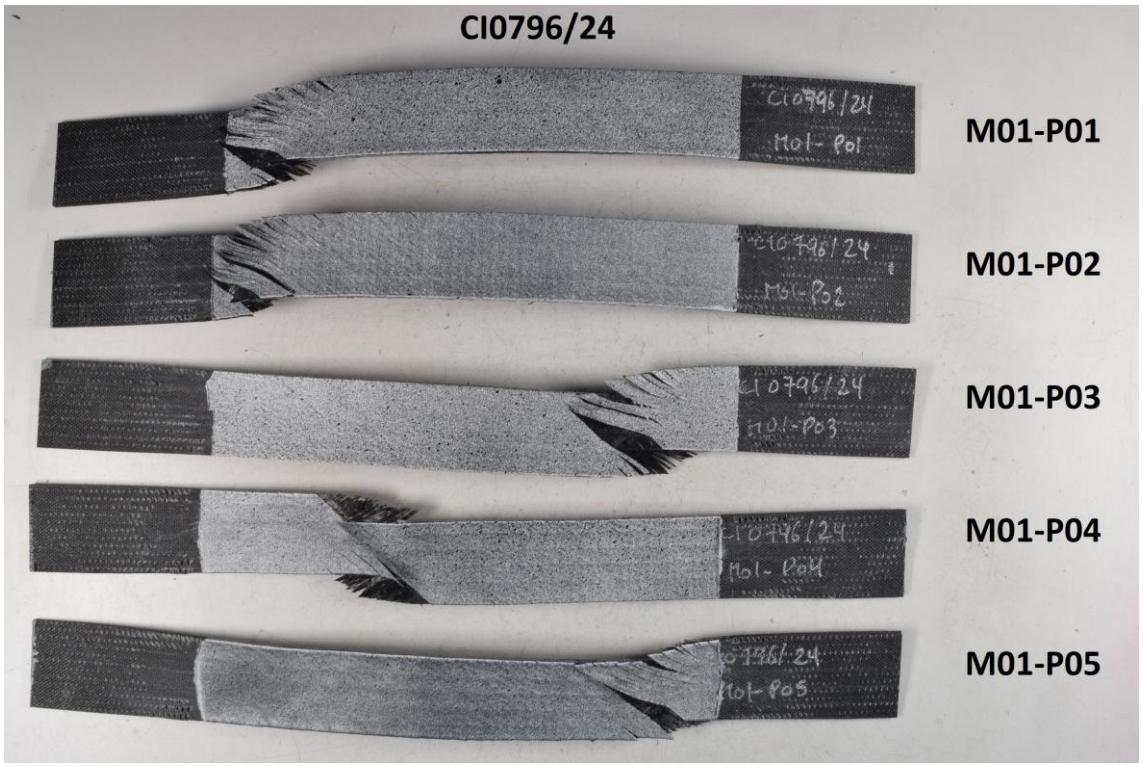

Figure 31. Failure mode for reference coupons – Batch 1. In-plane shear tests, RT.

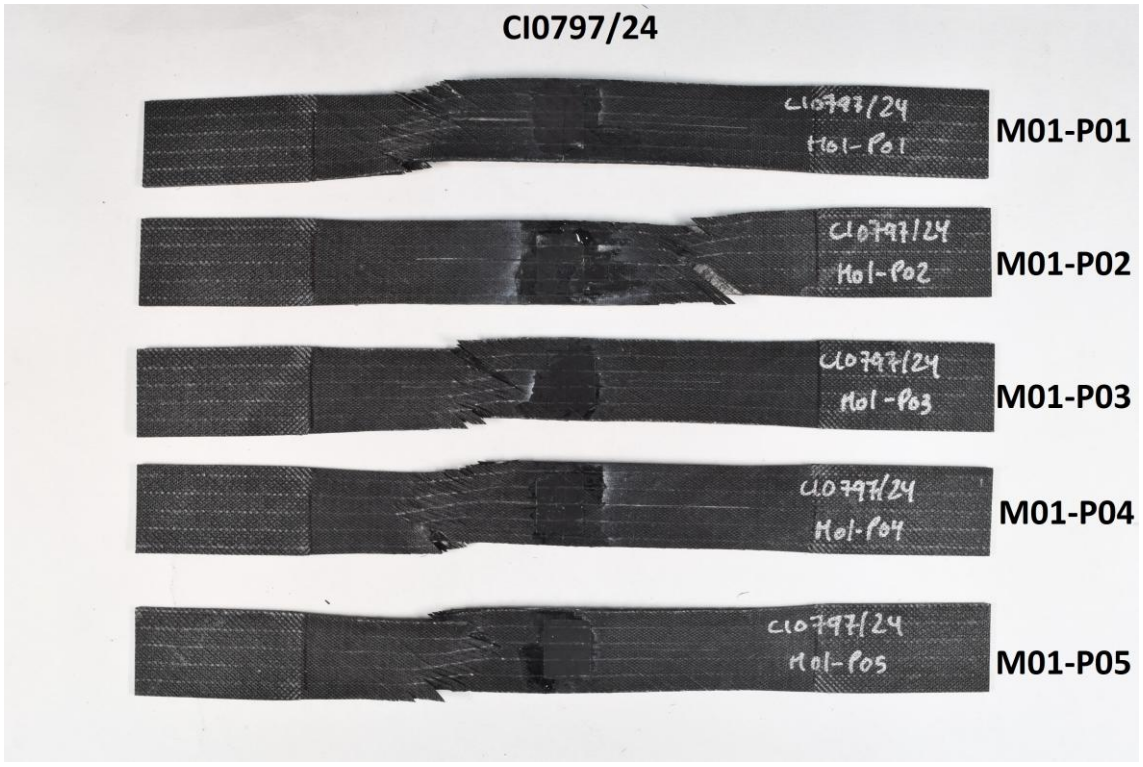

Figure 32. Failure mode for reference coupons – Batch 2. In-plane shear tests, RT.

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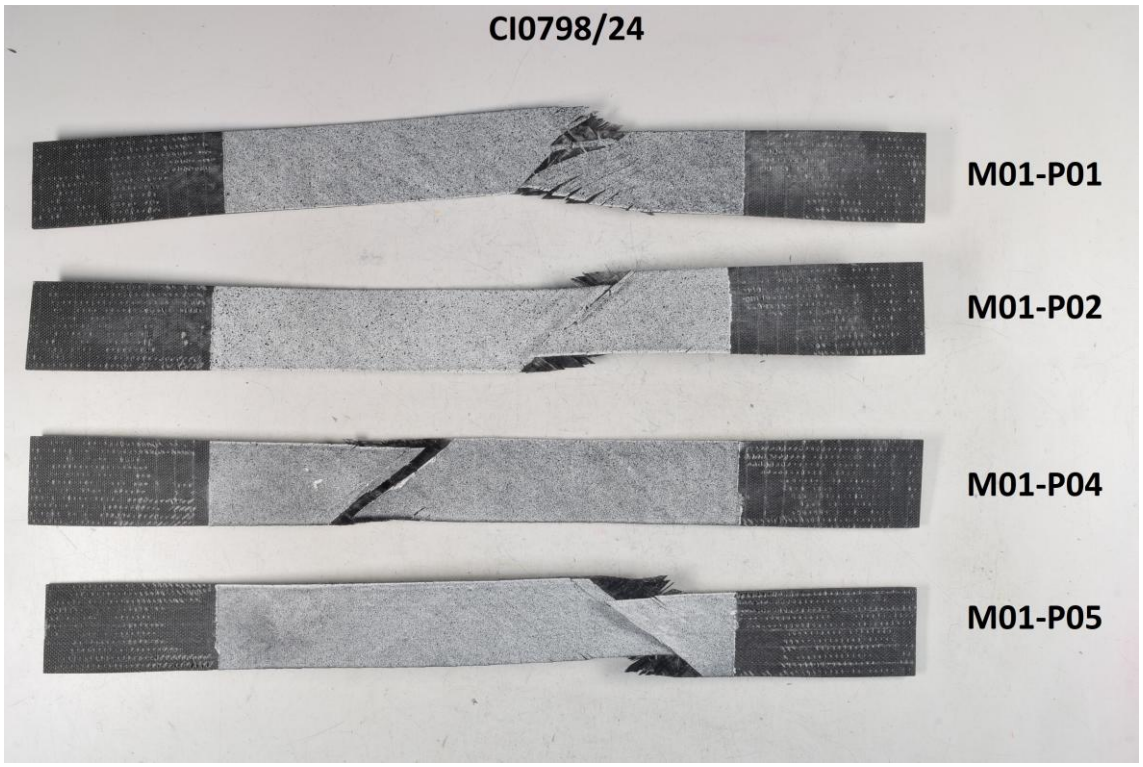

Figure 33. Failure mode for reference coupons – Batch 3. In-plane shear tests, RT.

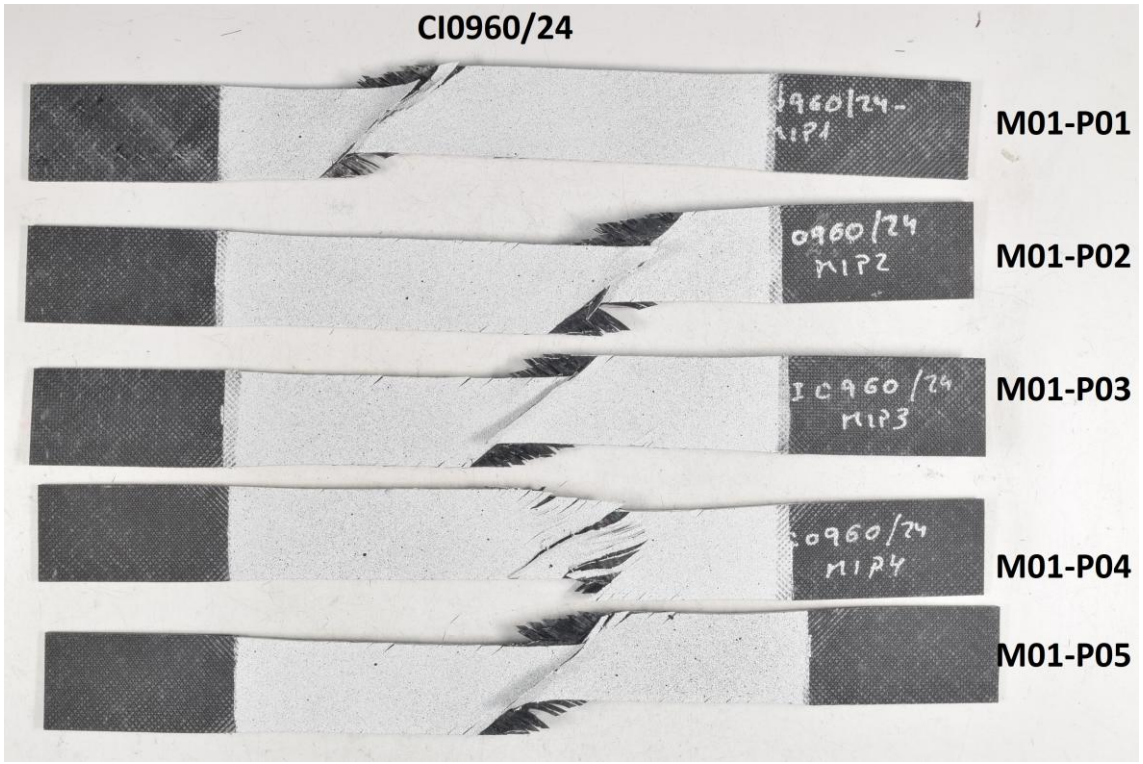

Figure 34. Failure mode for sensorised with microwires coupons – Batch 1. In-plane shear tests, RT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

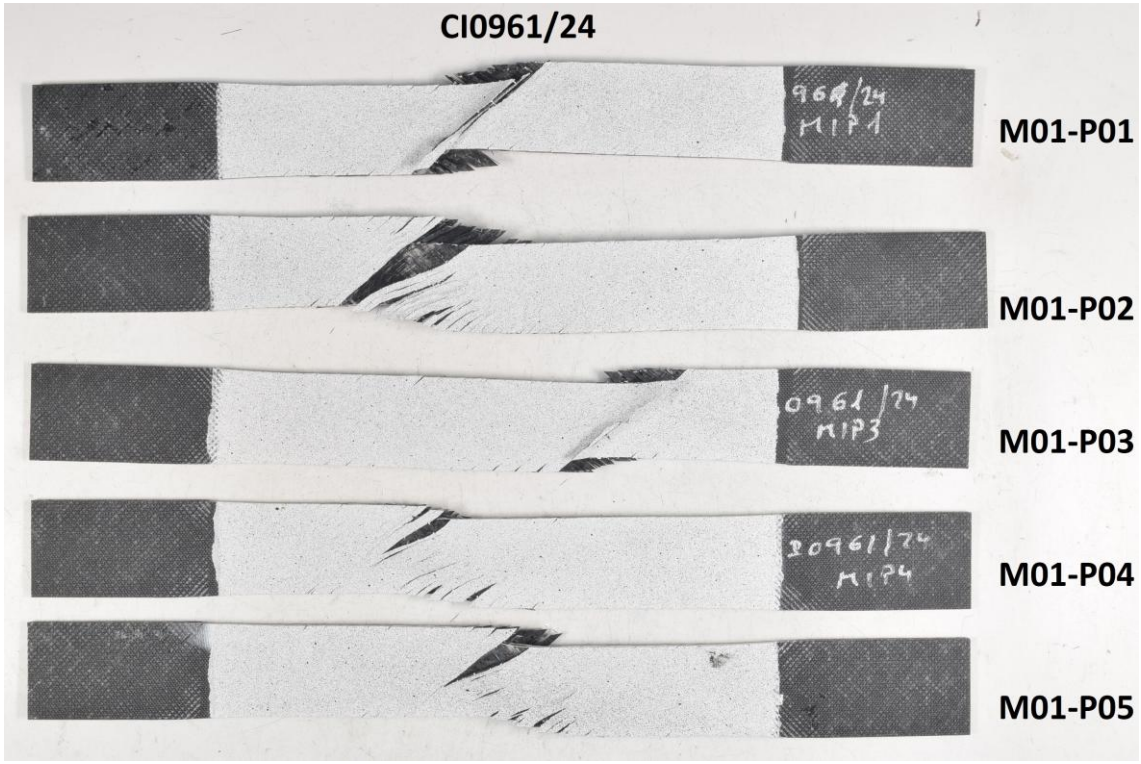

Figure 35. Failure mode for sensorised with microwires coupons – Batch 2. In-plane shear tests, RT.

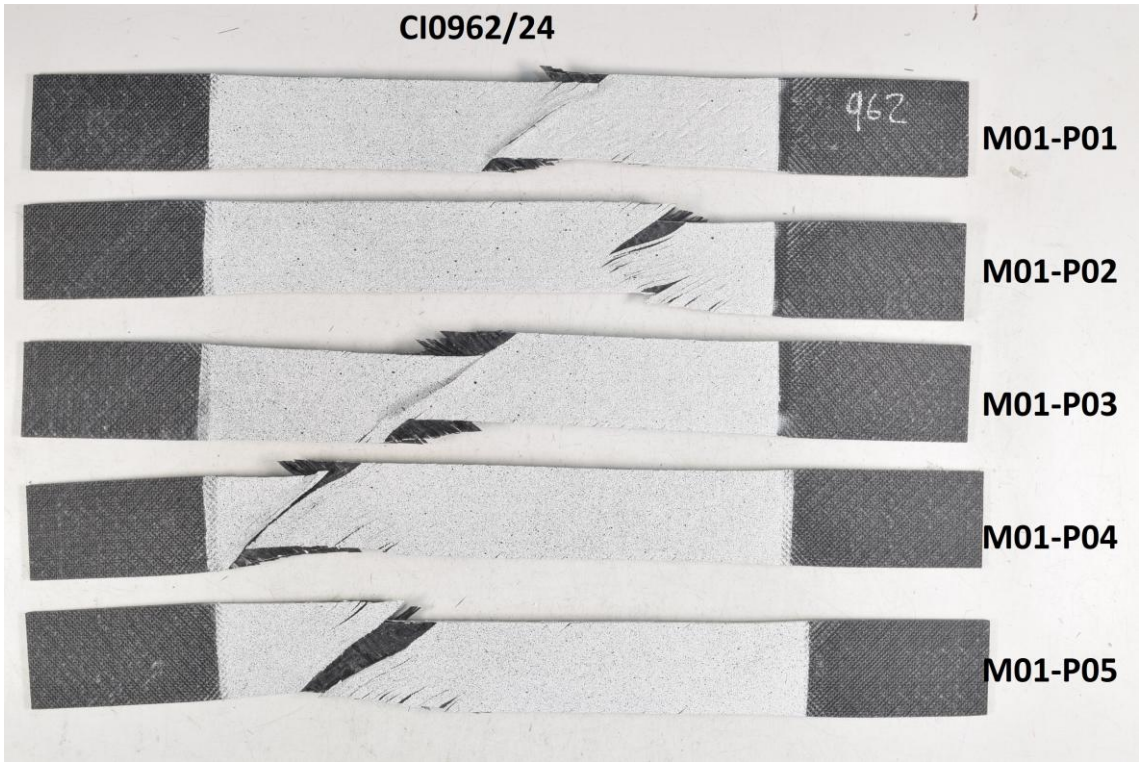

Figure 36. Failure mode for sensorised with microwires coupons – Batch 3. In-plane shear tests, RT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

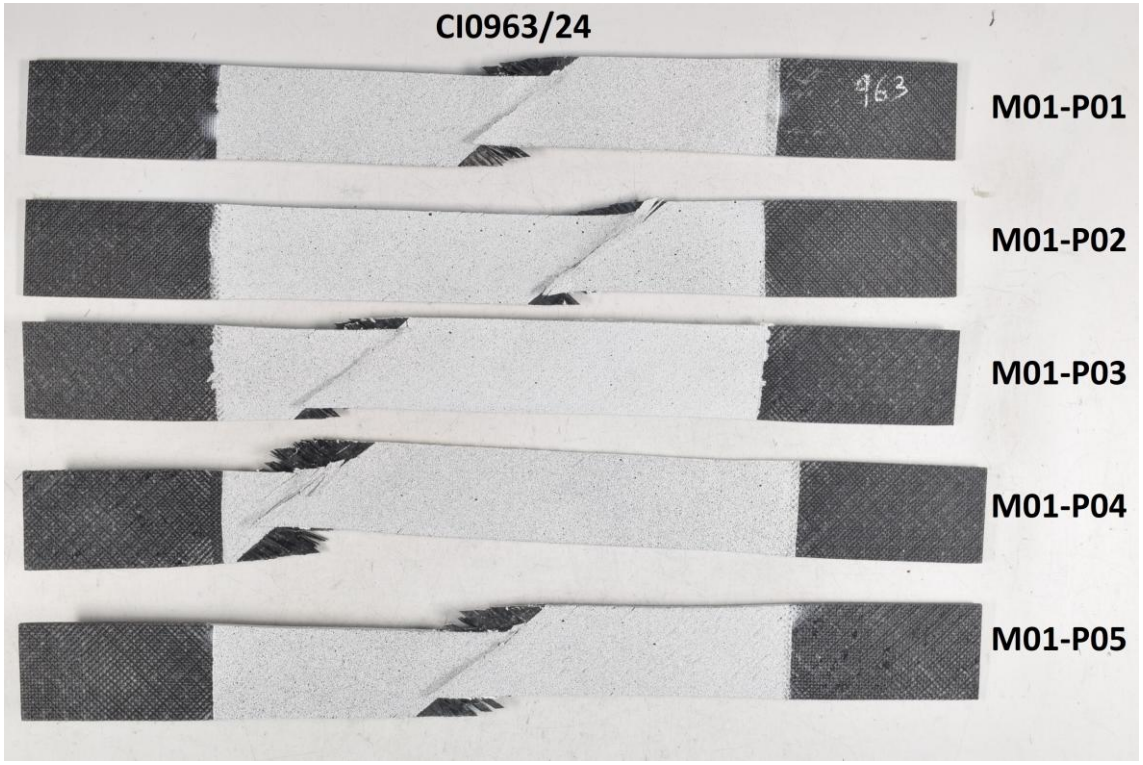

Figure 37. Failure mode for sensorised with microwires coupons – Batch 4. In-plane shear tests, RT.

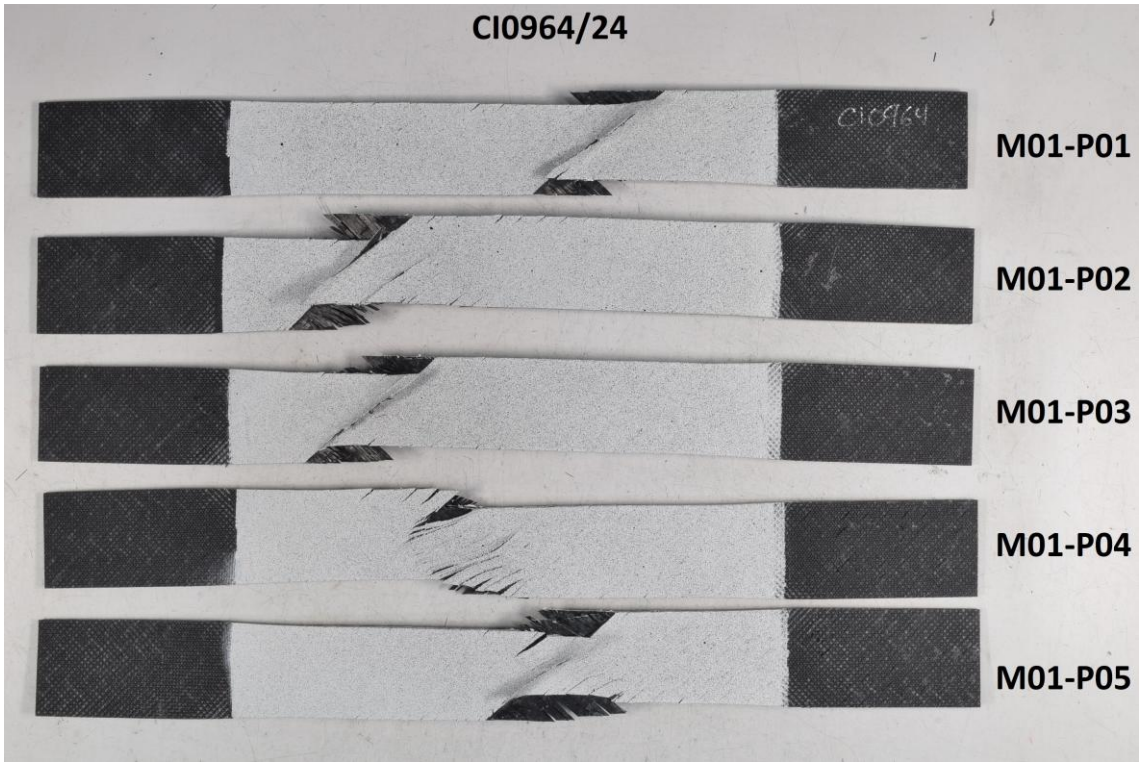

Figure 38. Failure mode for sensorised with microwires coupons – Batch 5. In-plane shear tests, RT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

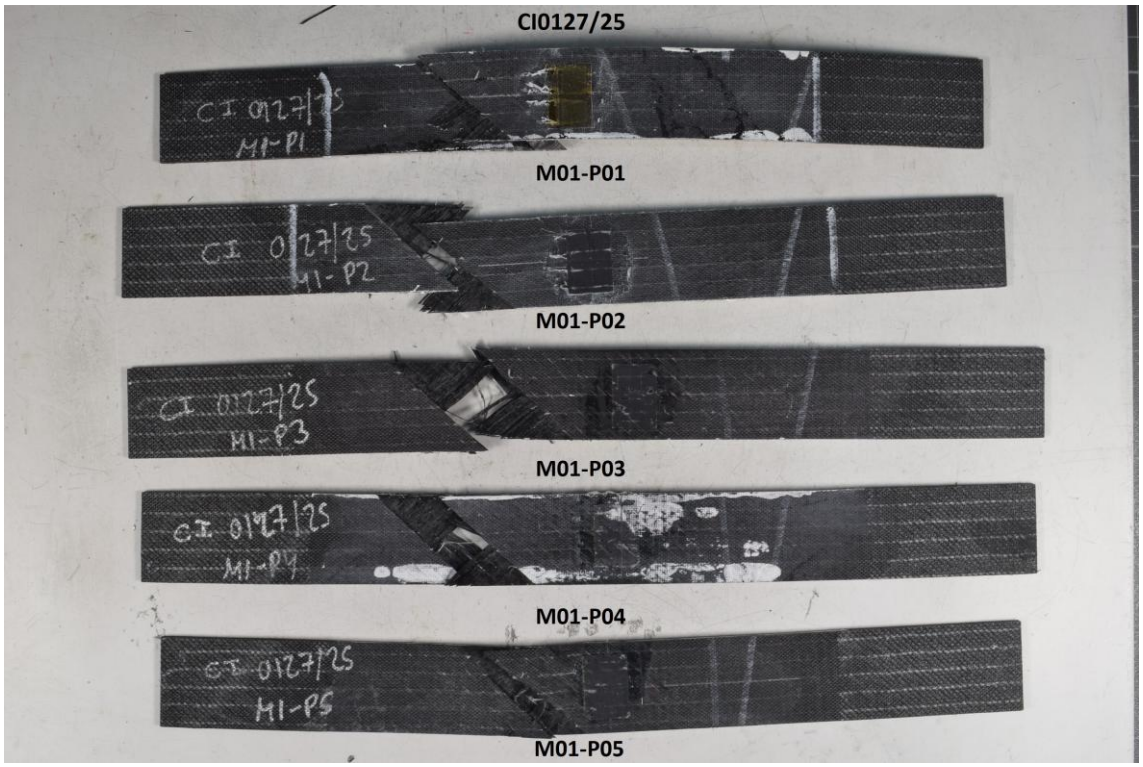

Figure 39. Failure mode for reference coupons – Batch 1. In-plane shear tests, HT.

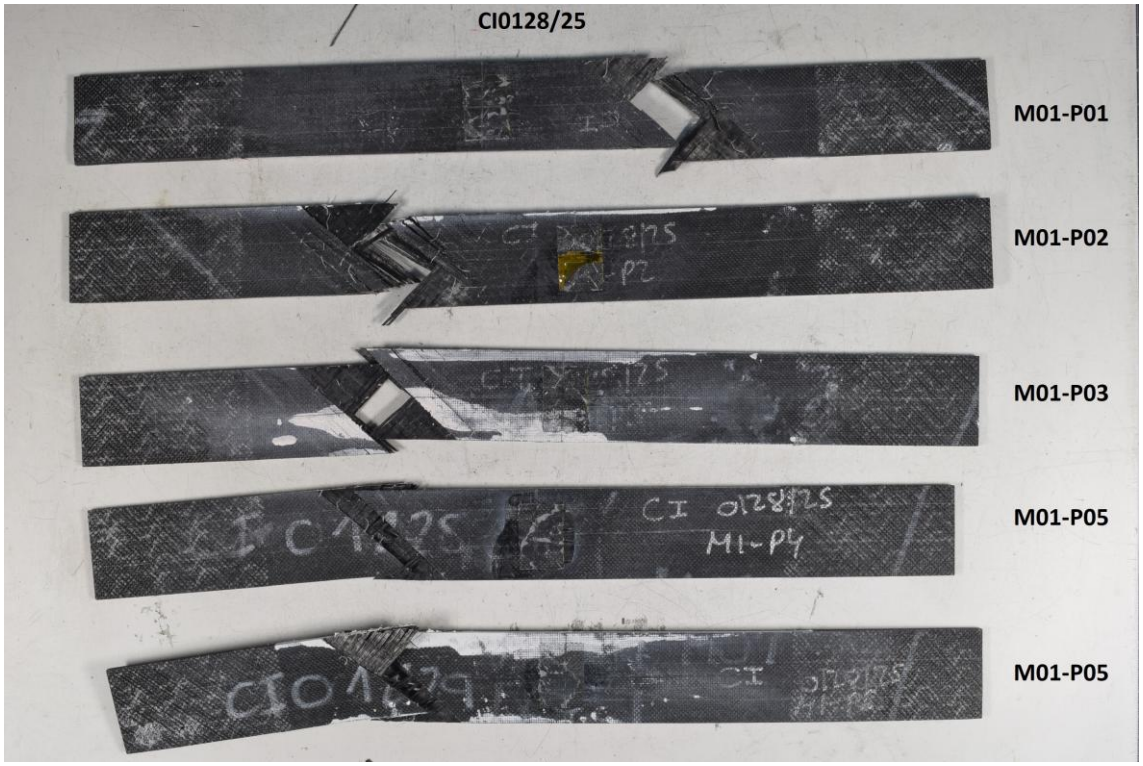

Figure 40. Failure mode for sensorised with microwires coupons – Batch 1. In-plane shear tests, HT.

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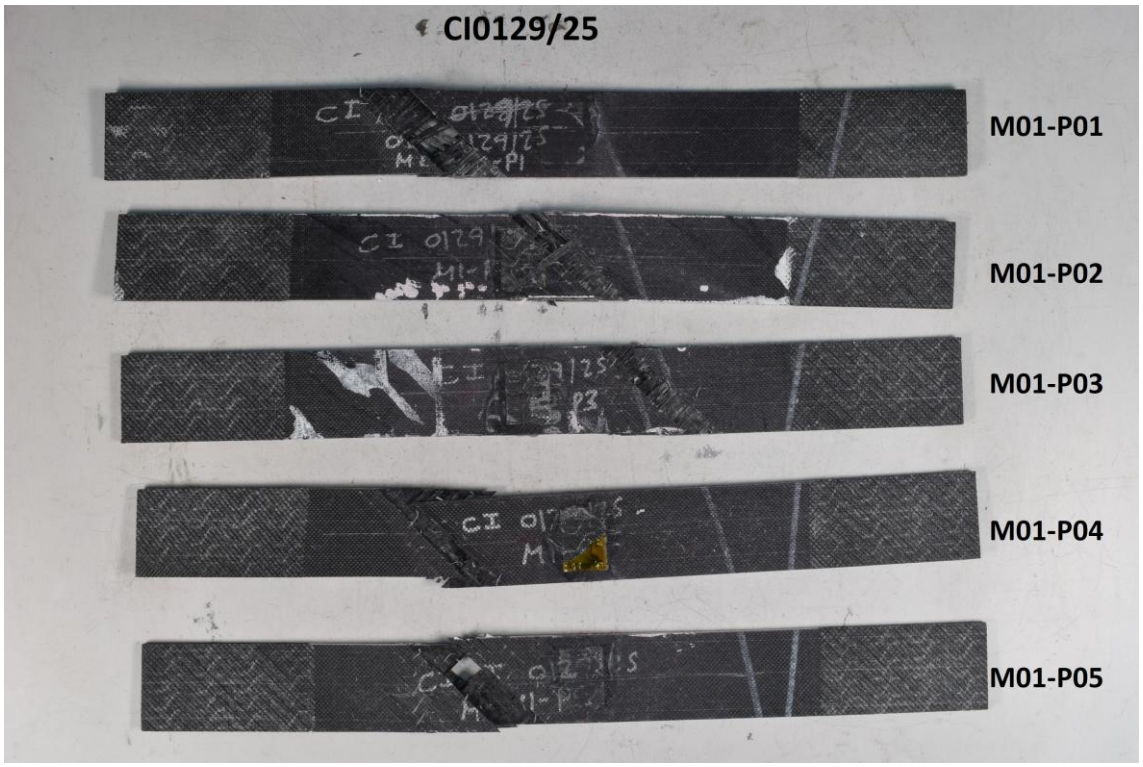

Figure 41. Failure mode for sensorised with microwires coupons – Batch 2. In-plane shear tests, HT.

Figure 42. Failure mode for sensorised with microwires coupons – Batch 3. In-plane shear tests, HT.

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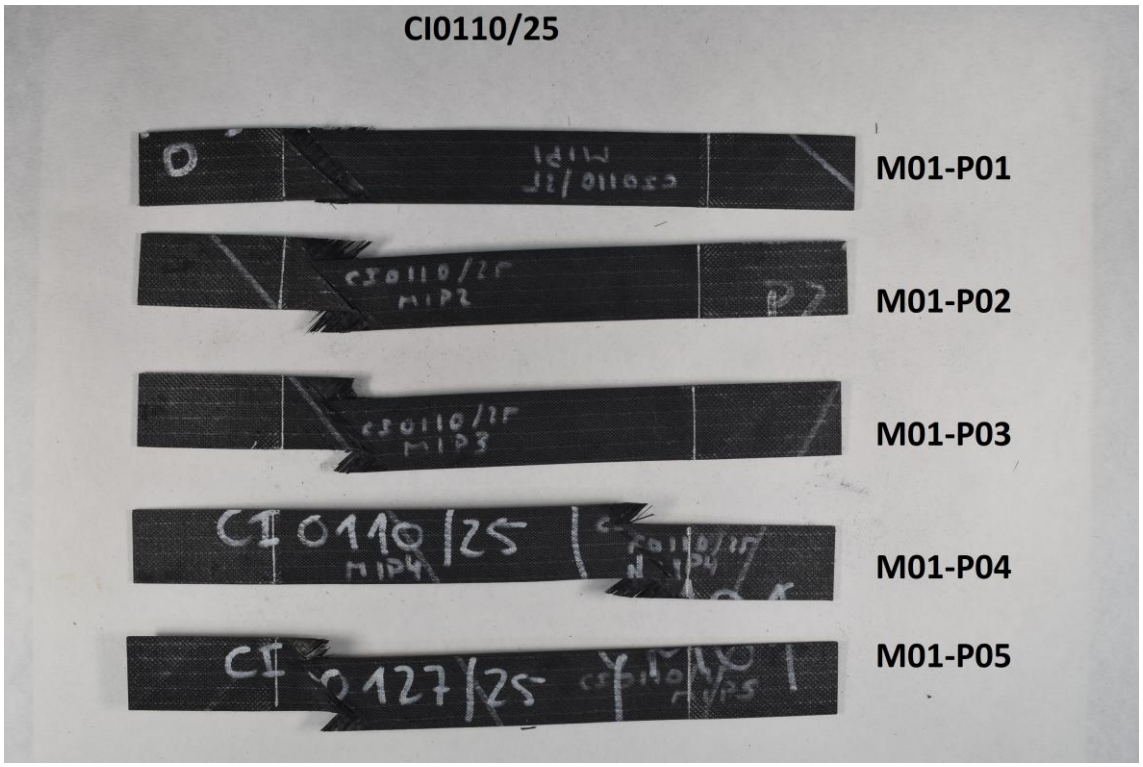

Figure 43. Failure mode for reference coupons – Batch 1. In-plane shear tests, LT.

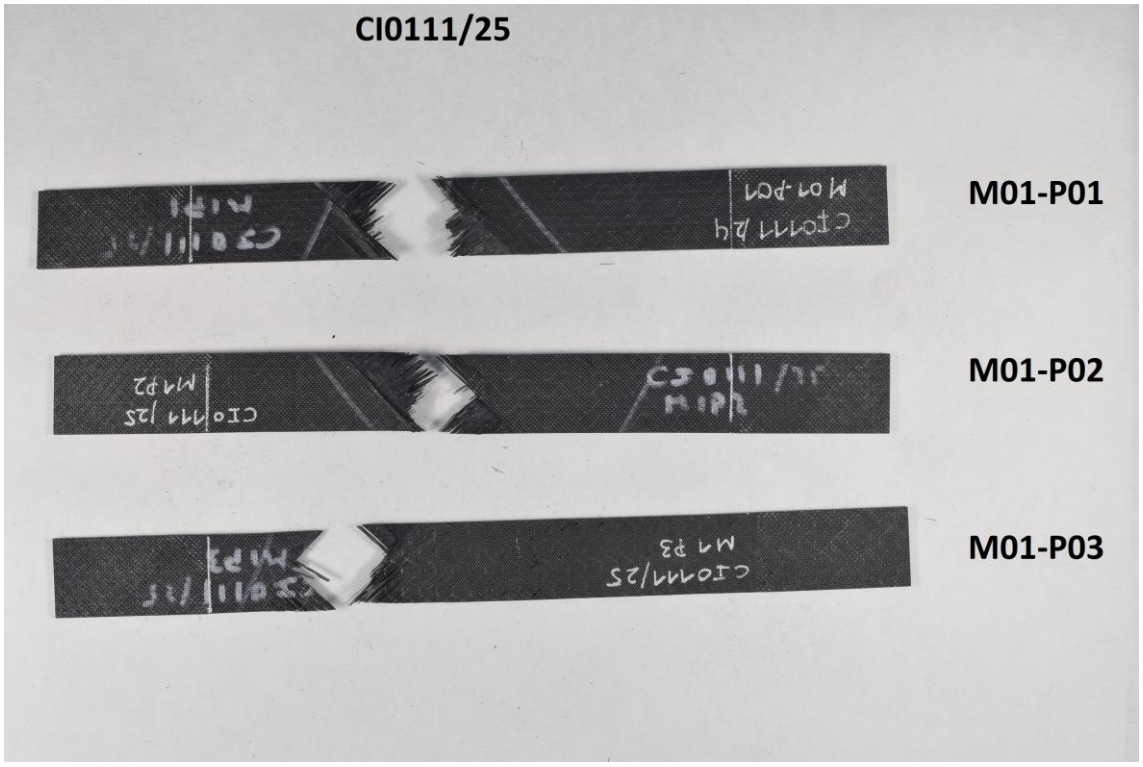

Figure 44. Failure mode for sensorised with microwires coupons – Batch 1. In-plane shear tests, LT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

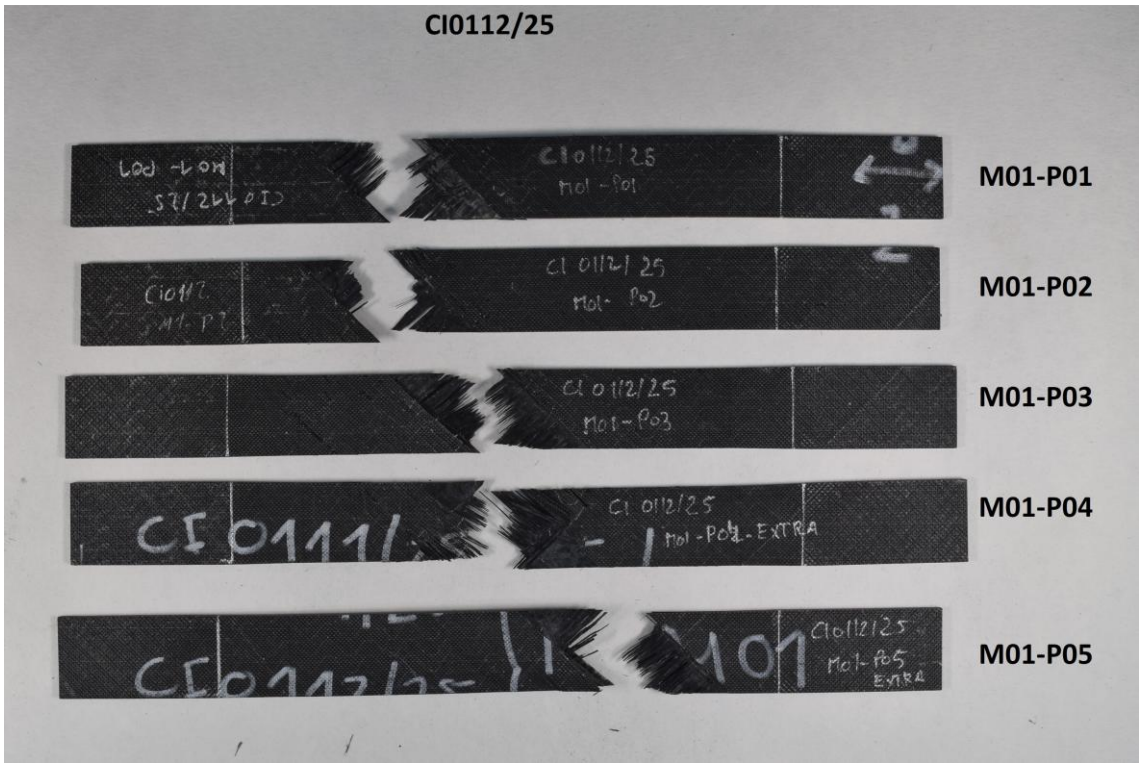

Figure 45. Failure mode for sensorised with microwires coupons – Batch 2. In-plane shear tests, LT.

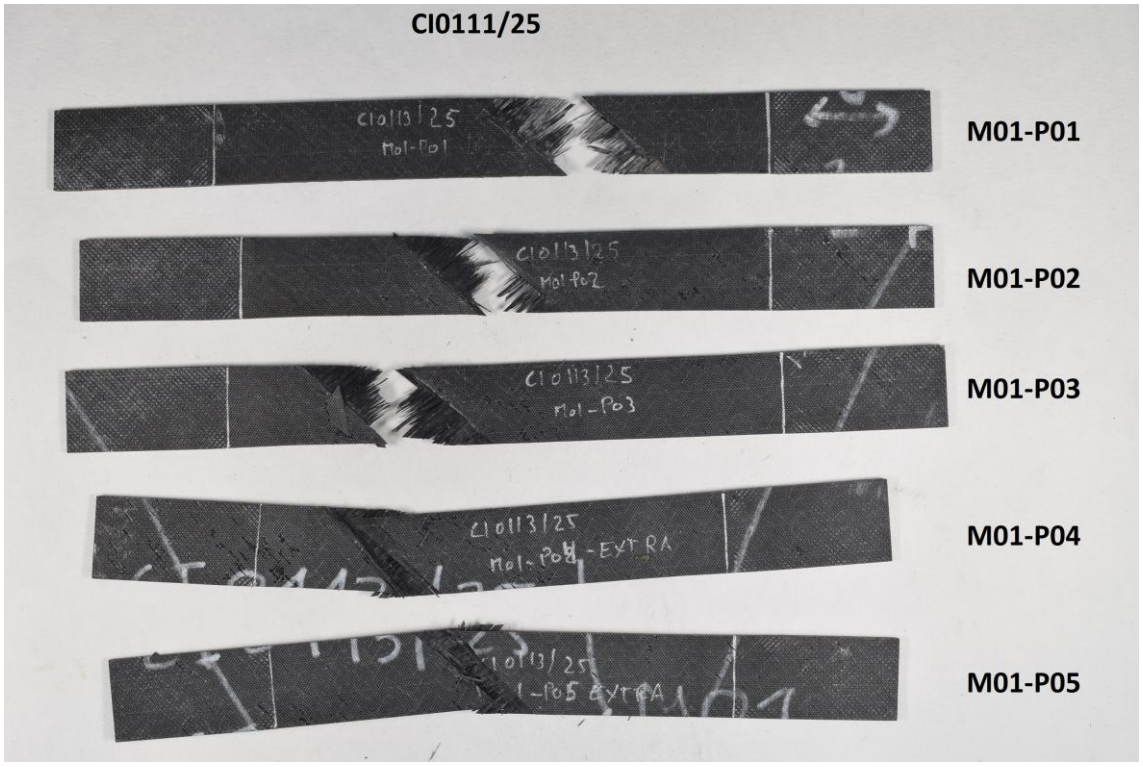

Figure 46. Failure mode for sensorised with microwires coupons – Batch 3. In-plane shear tests, LT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

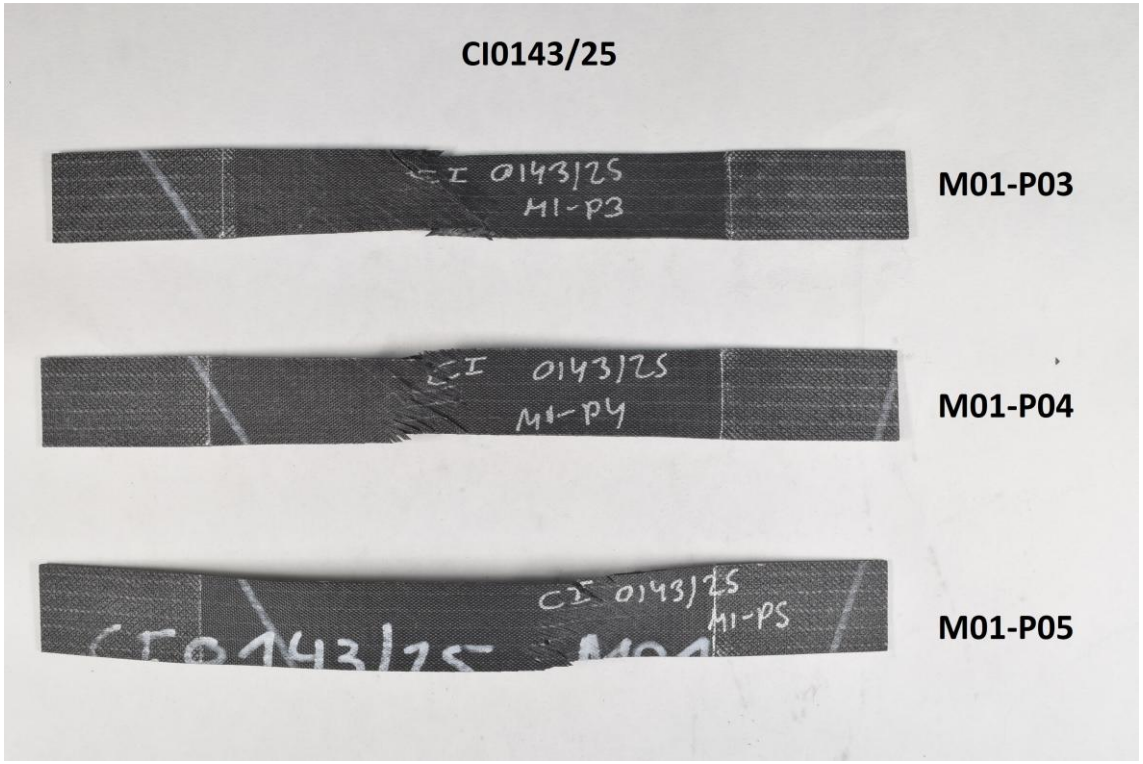

Figure 47. Failure mode for reference coupons – Batch 1. In-plane shear tests, WET/RT.

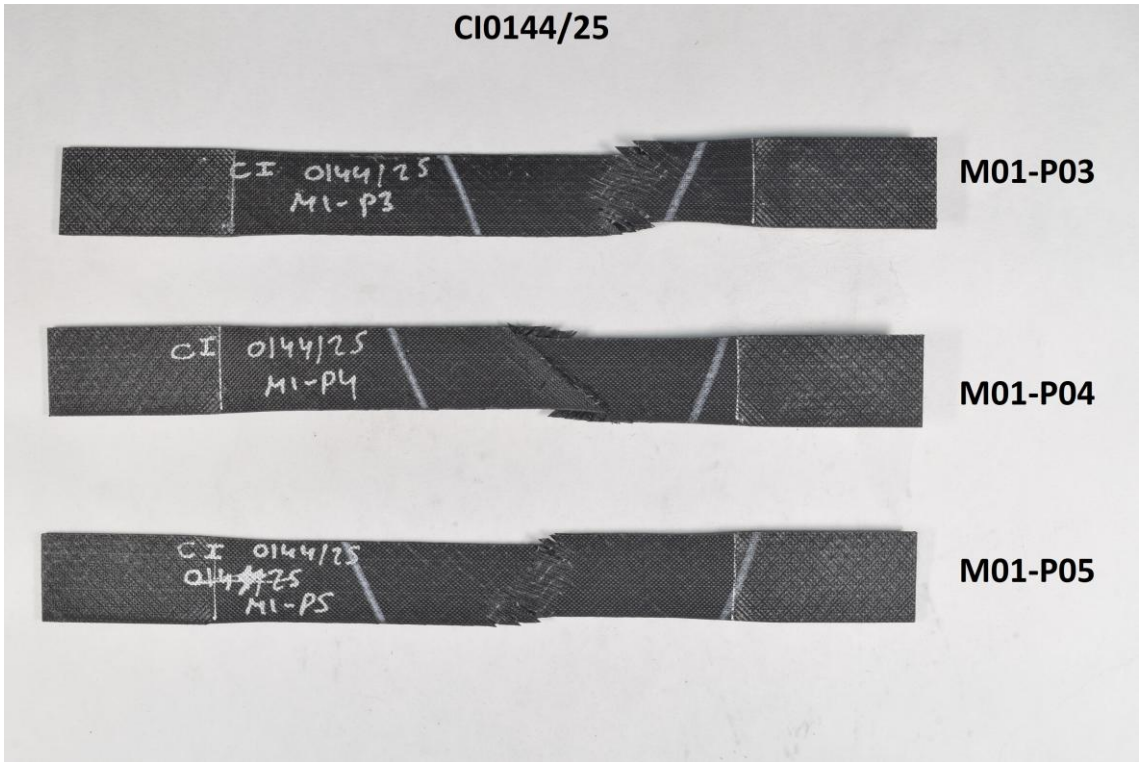

Figure 48. Failure mode for sensorised with microwires coupons – Batch 1. In-plane shear tests, WET/RT.

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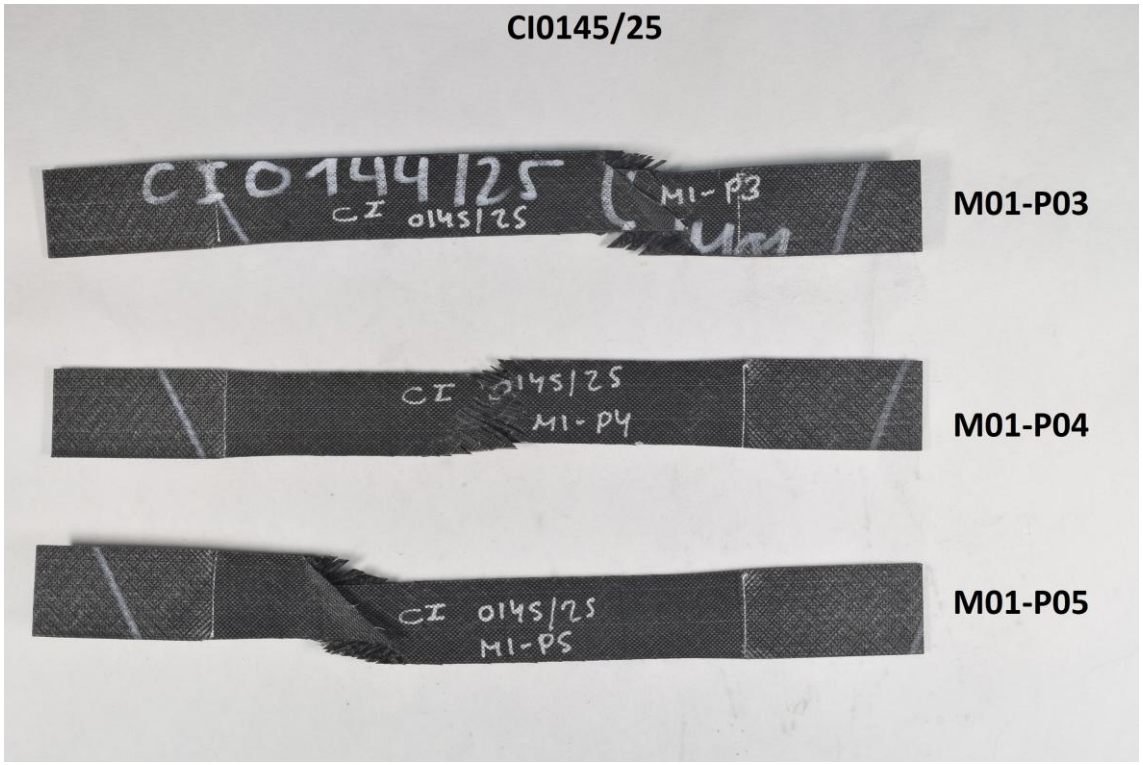

Figure 49. Failure mode for sensorised with microwires coupons – Batch 2. In-plane shear tests, WET/RT.

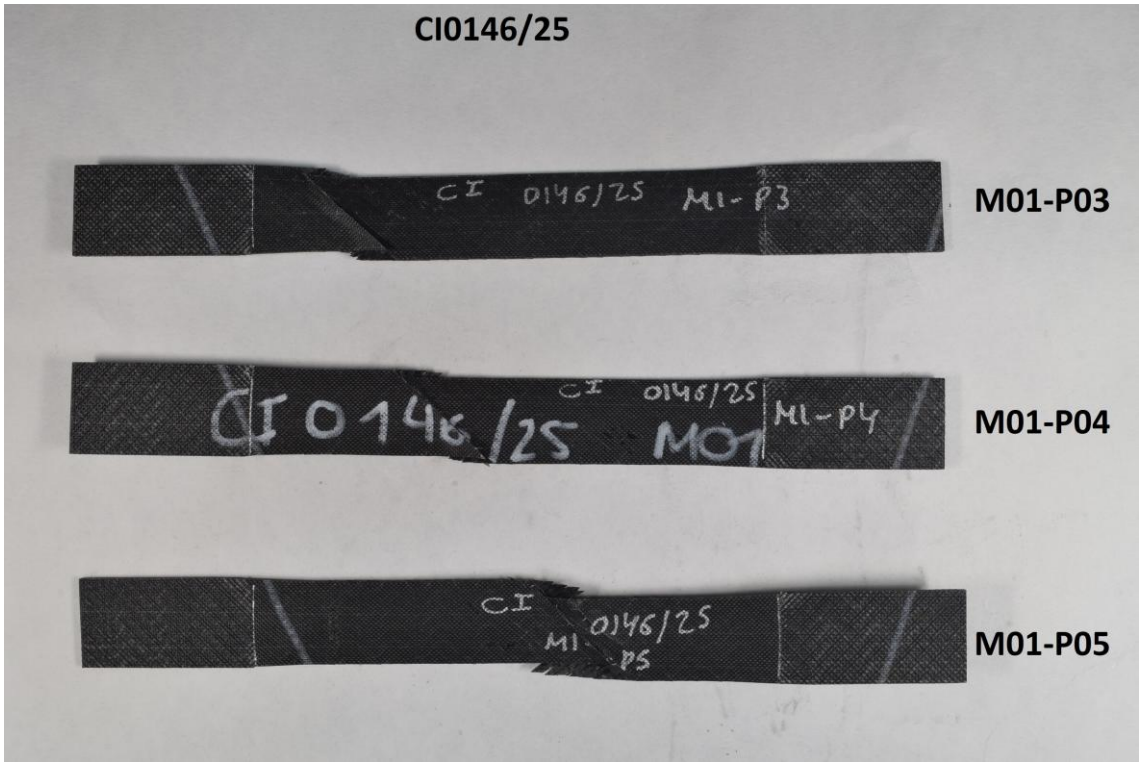

Figure 50. Failure mode for sensorised with microwires coupons – Batch 3. In-plane shear tests, WET/RT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

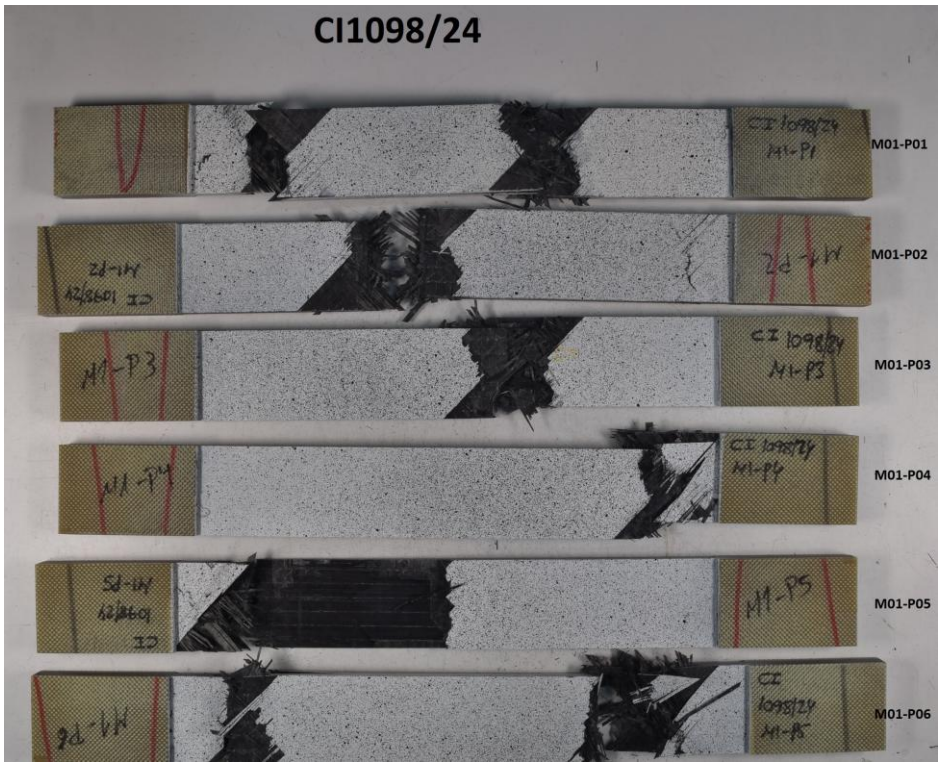

Figure 51. Failure mode for reference coupons – Batch 1. Tensile tests (plain), RT.

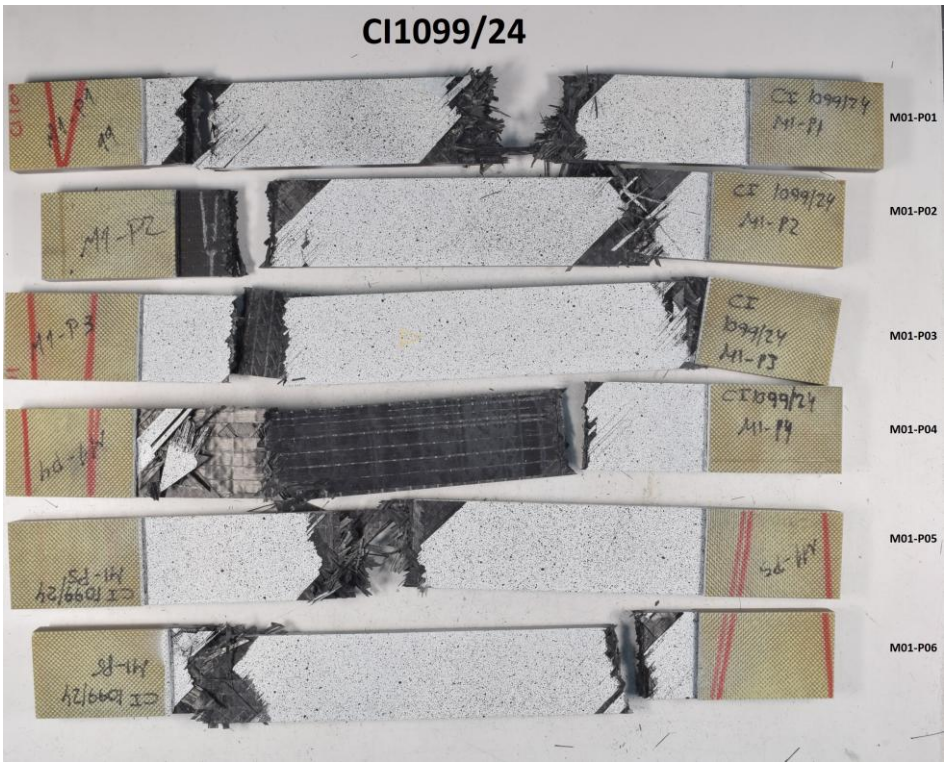

Figure 52. Failure mode for reference coupons – Batch 2. Tensile tests (plain), RT.

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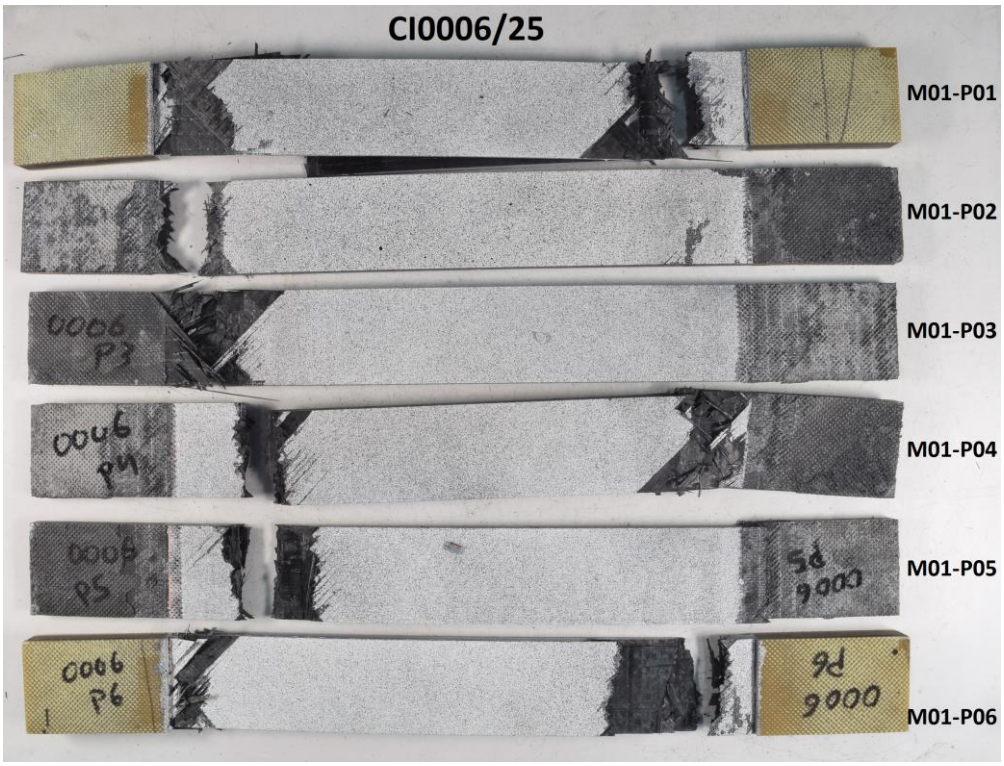

Figure 53. Failure mode for reference coupons – Batch 3. Tensile tests (plain), RT.

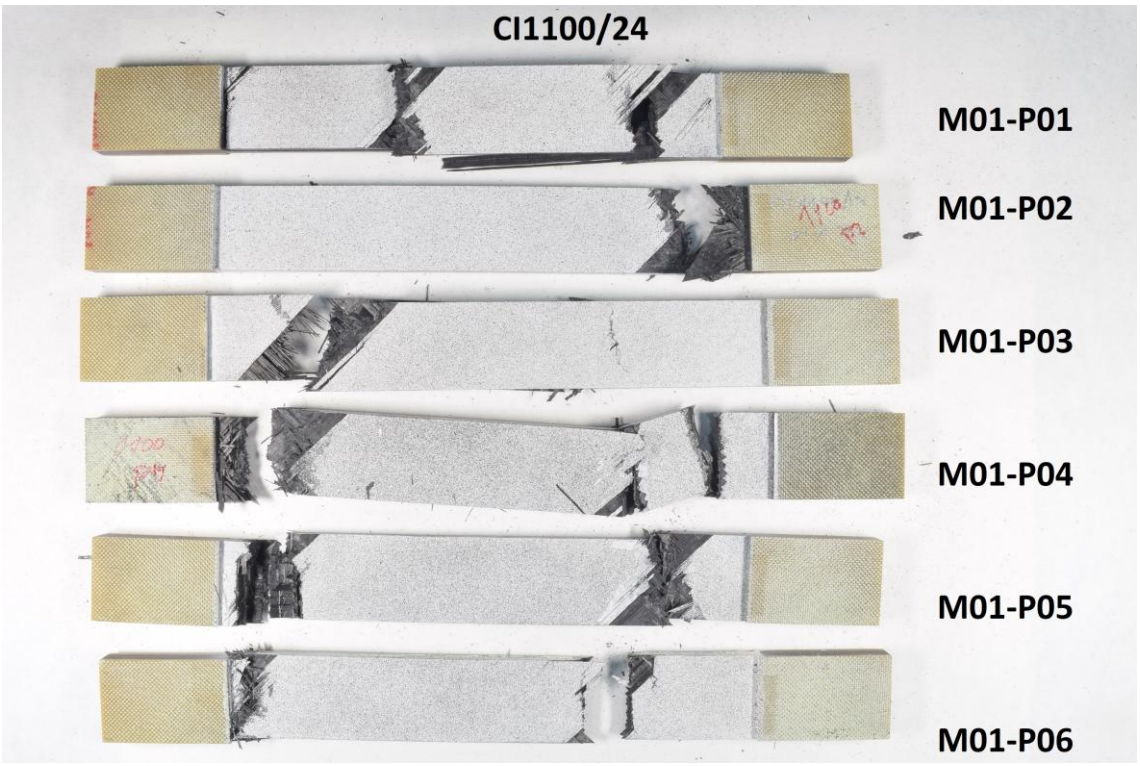

Figure 54. Failure mode for sensorised with microwires coupons – Batch 1. Tensile tests (plain), RT.

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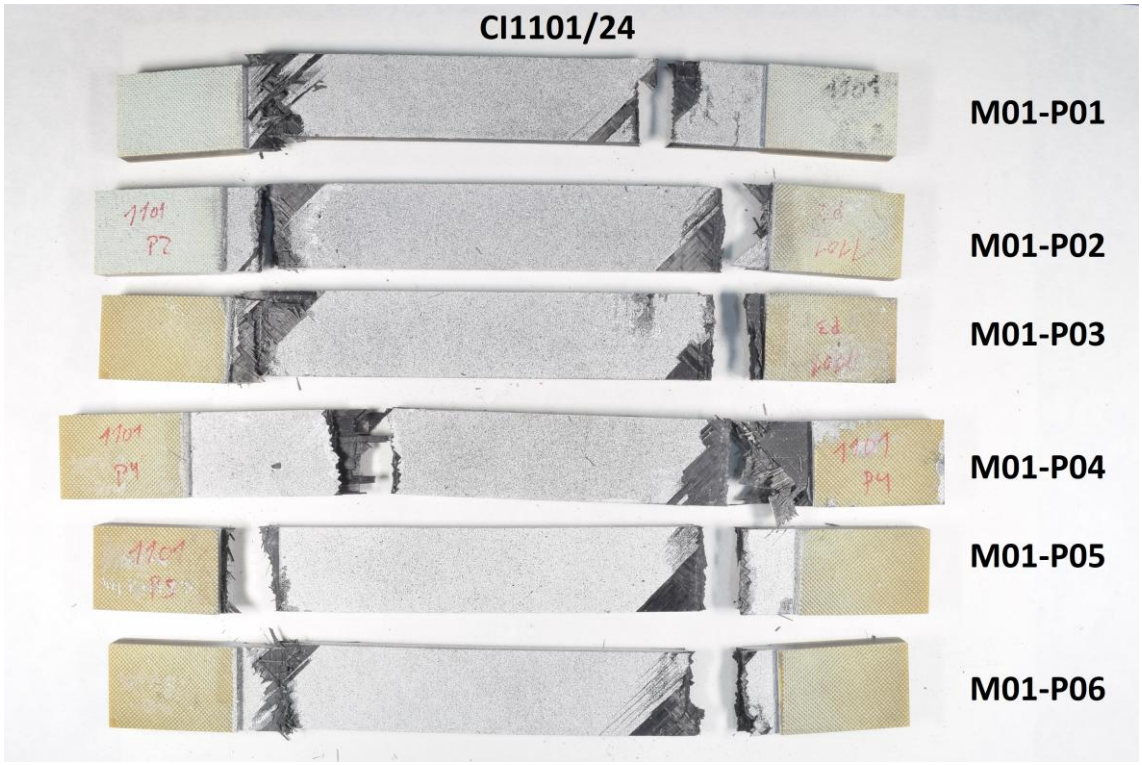

Figure 55. Failure mode for sensorised with microwires coupons – Batch 2. Tensile tests (plain), RT.

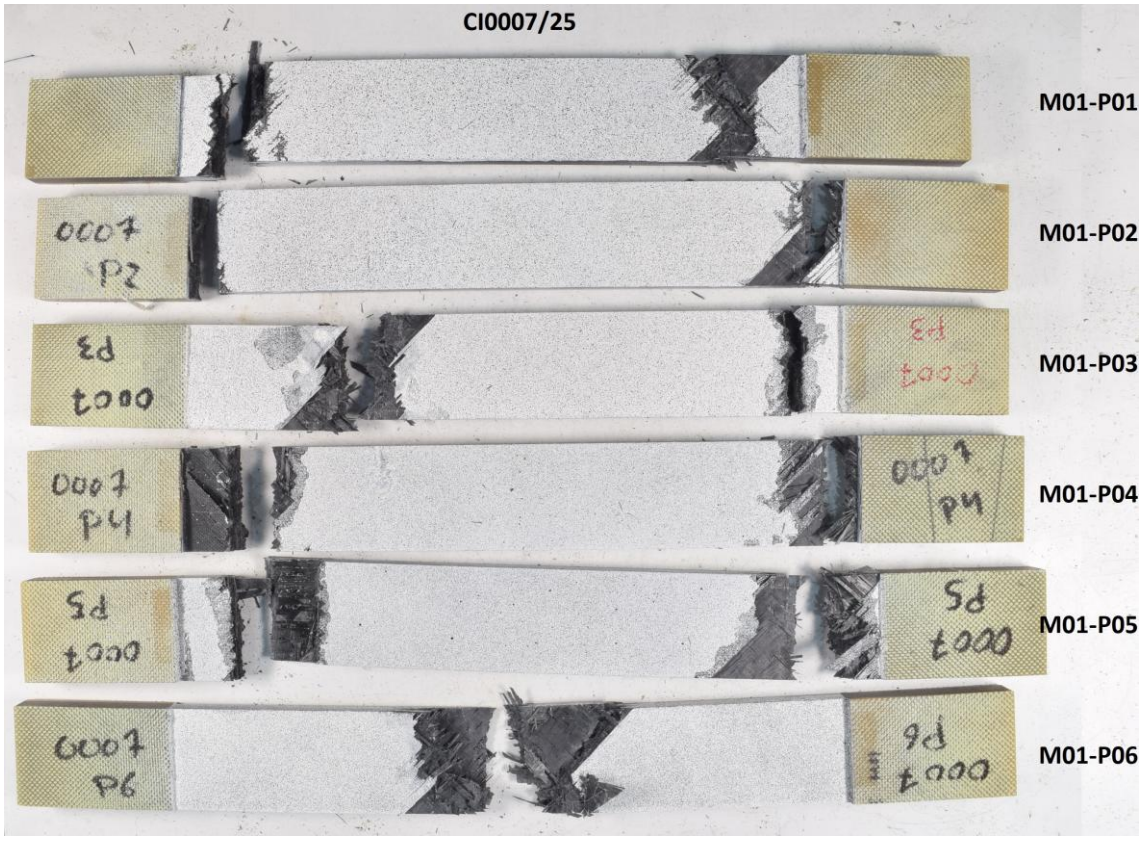

Figure 56. Failure mode for sensorised with microwires coupons – Batch 3. Tensile tests (plain), RT.

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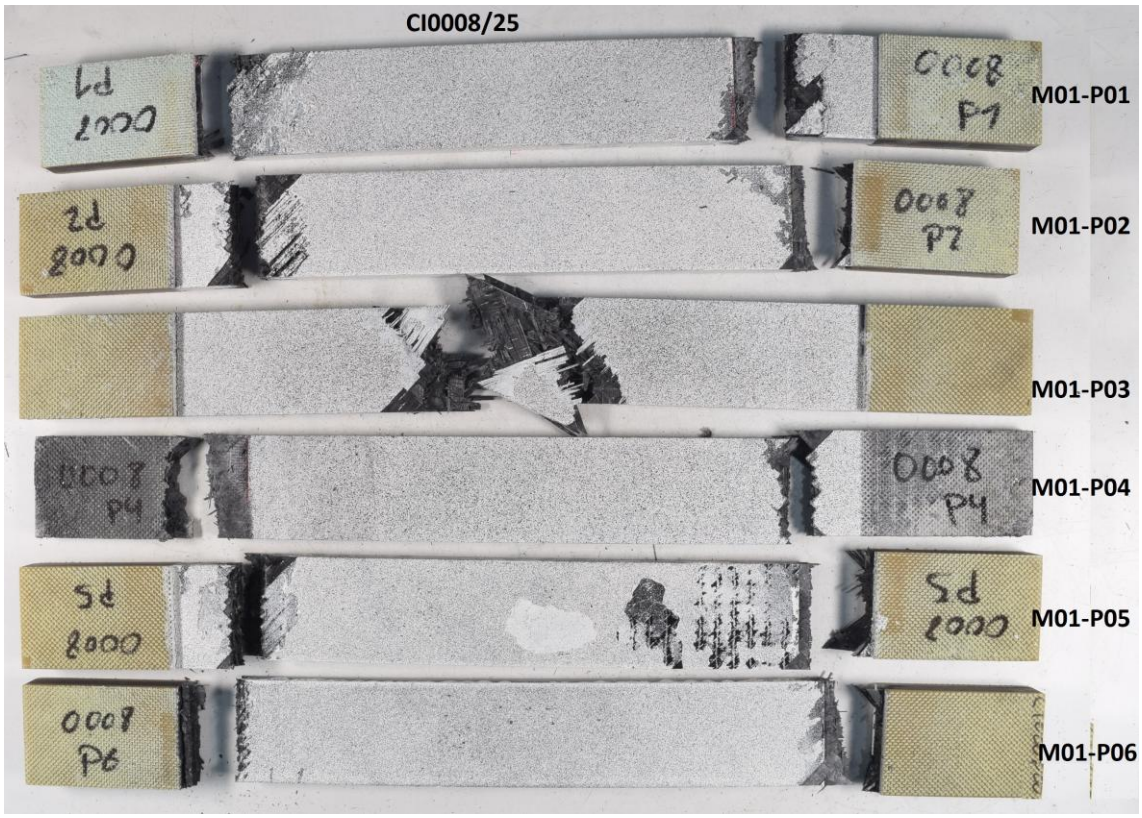

Figure 57. Failure mode for sensorised with microwires coupons – Batch 4. Tensile tests (plain), RT.

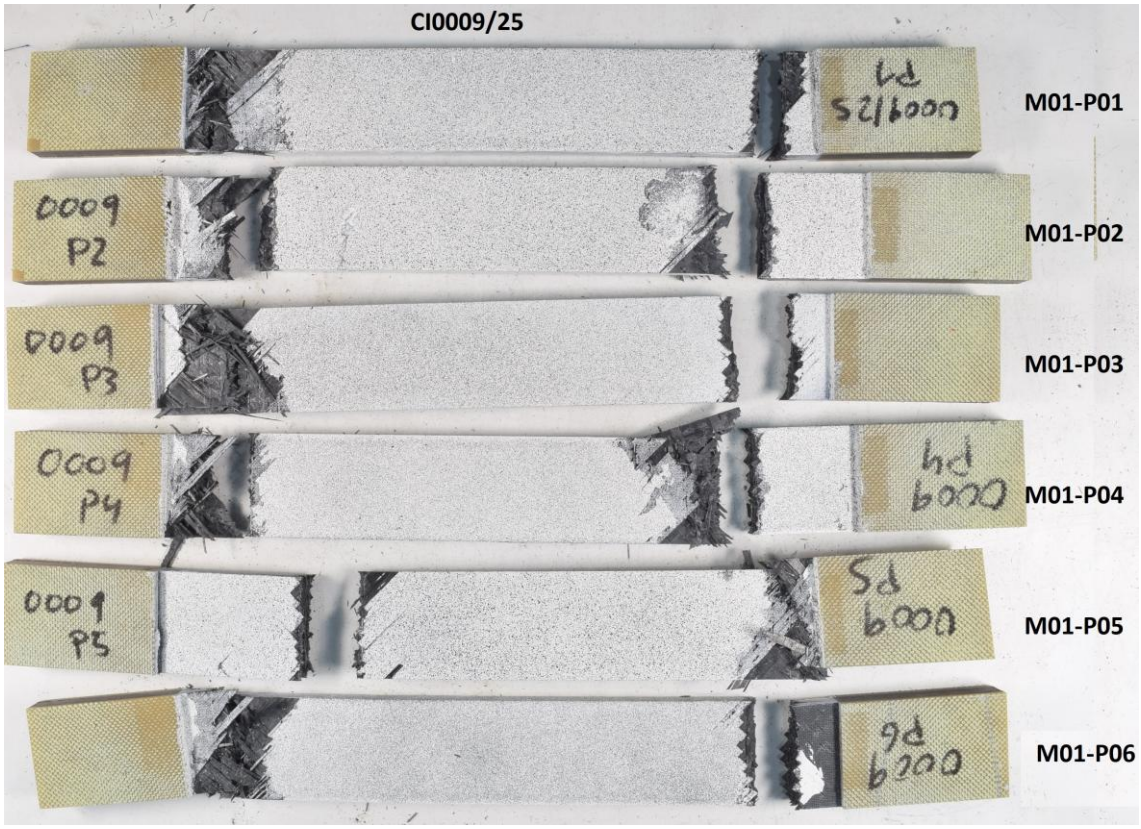

Figure 58. Failure mode for sensorised with microwires coupons – Batch 5. Tensile tests (plain), RT.

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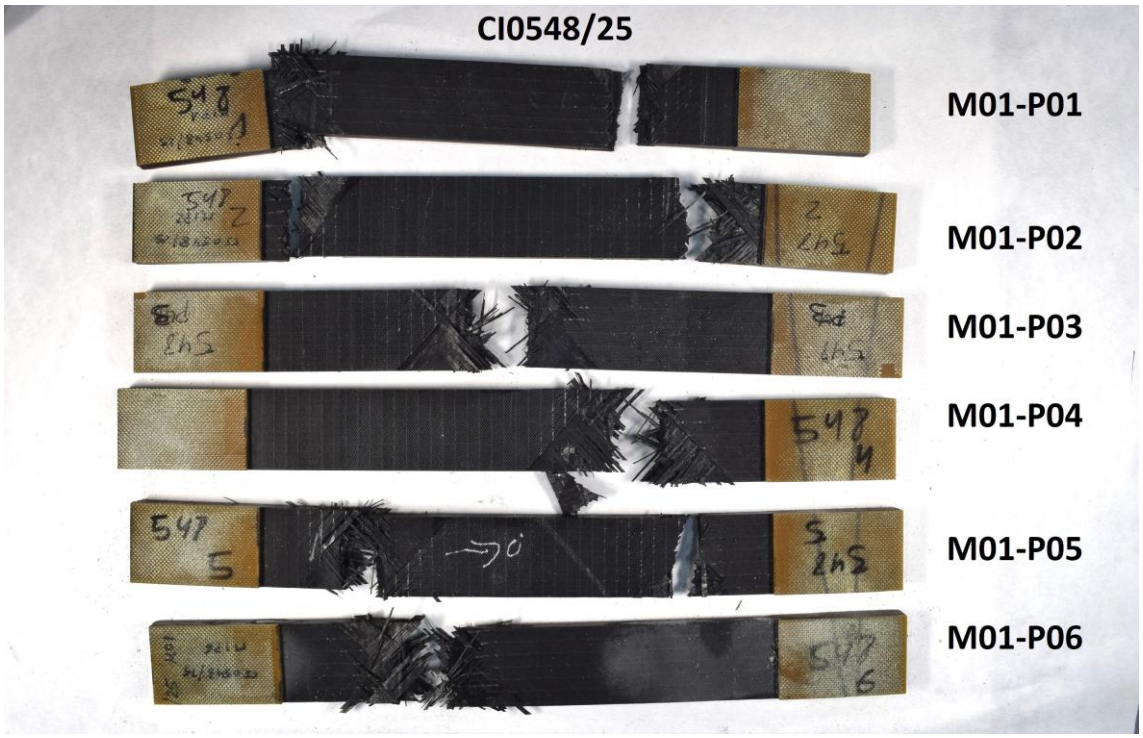

Figure 59. Failure mode for reference coupons – Batch 1. Tensile tests (plain), LT.

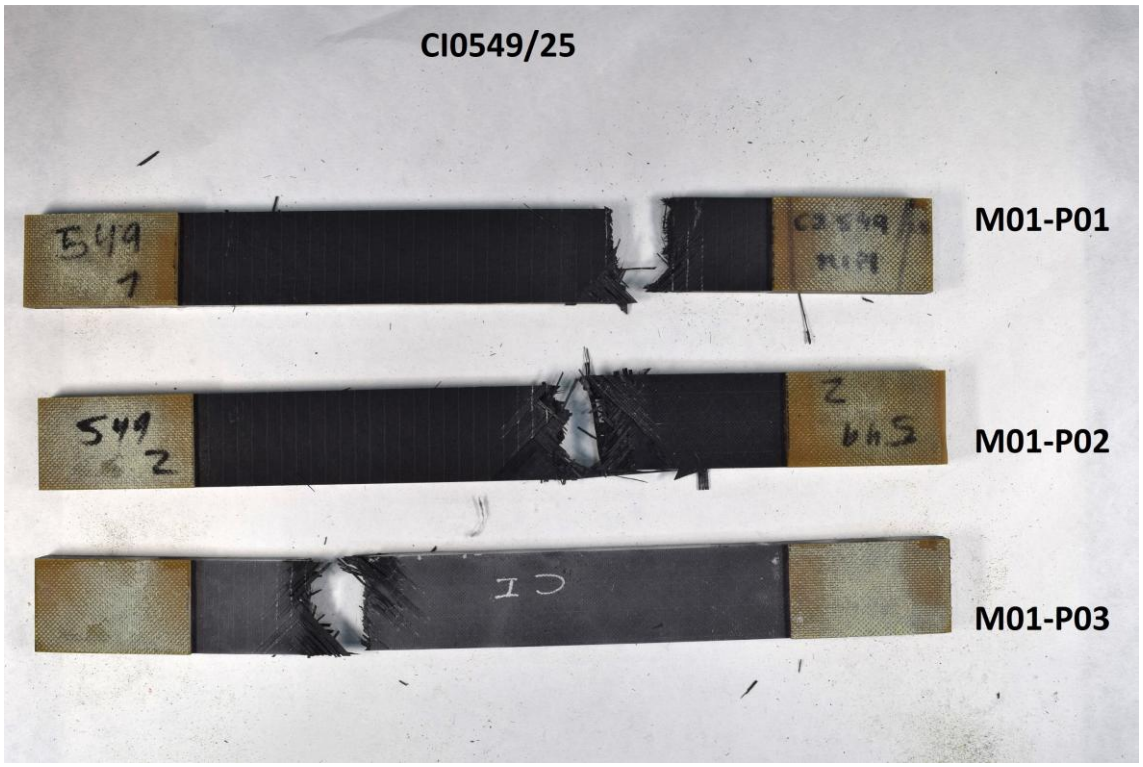

Figure 60. Failure mode for sensorised with microwires coupons – Batch 1. Tensile tests (plain), LT.

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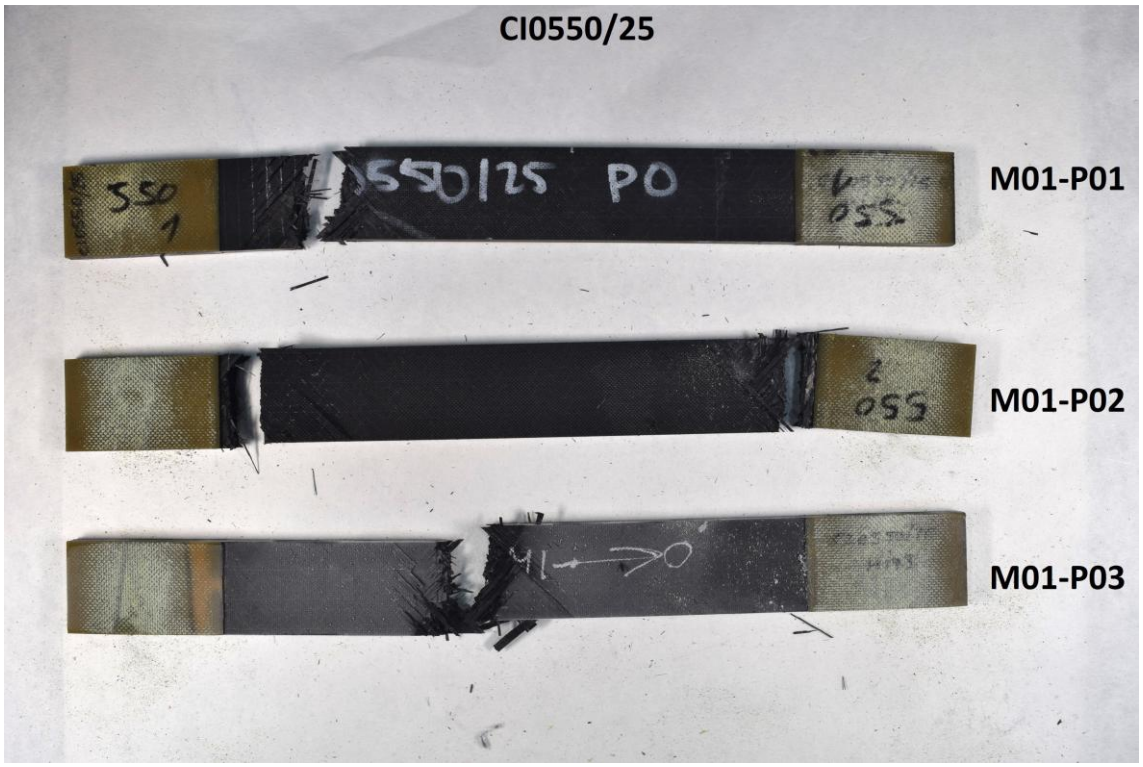

Figure 61. Failure mode for sensorised with microwires coupons – Batch 2. Tensile tests (plain), LT.

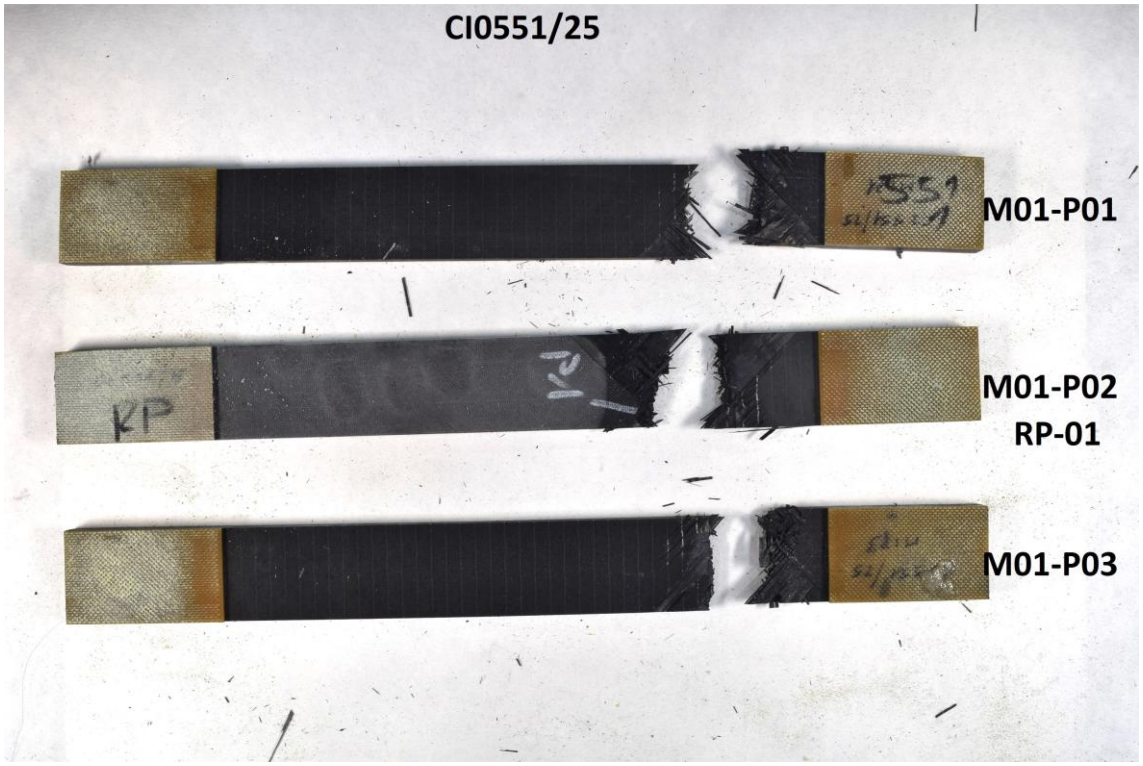

Figure 62. Failure mode for sensorised with microwires coupons – Batch 3. Tensile tests (plain), LT.

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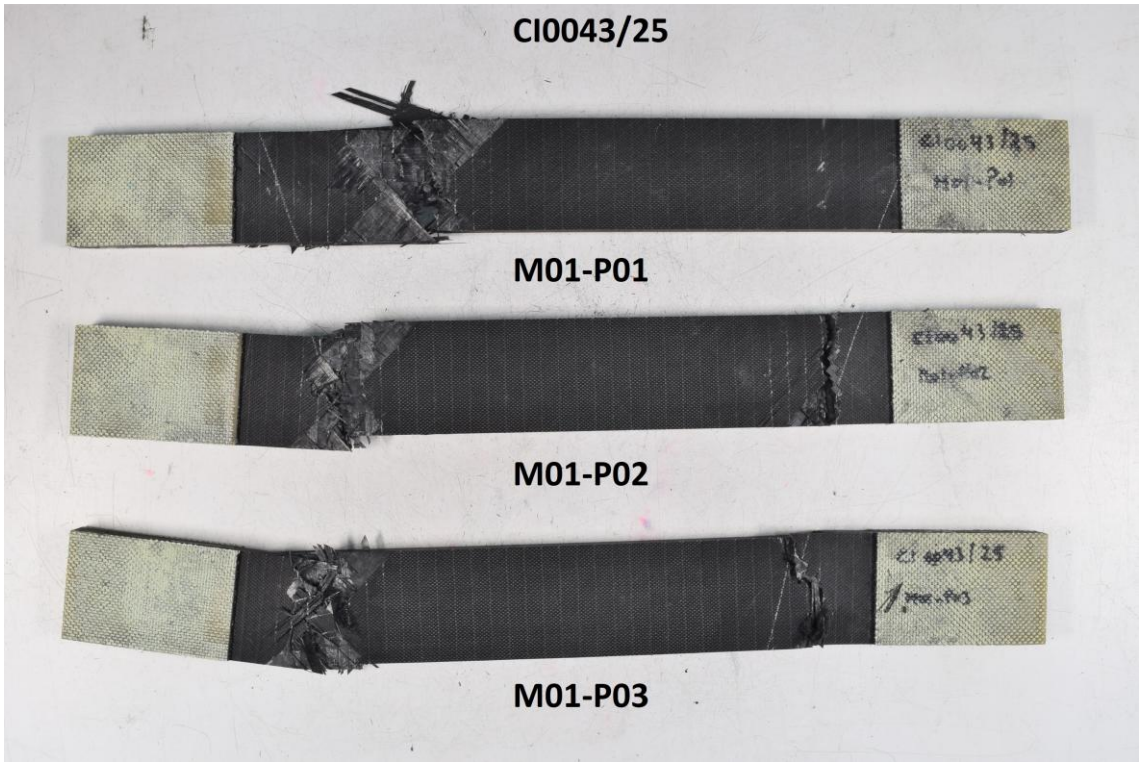

Figure 63. Failure mode for reference coupons – Batch 1. Tensile tests (plain), WET/RT.

Figure 64. Failure mode for sensorised with microwires coupons – Batch 1. Tensile tests (plain), WET/RT.

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Figure 65. Failure mode for sensorised with microwires coupons – Batch 2. Tensile tests (plain), WET/RT.

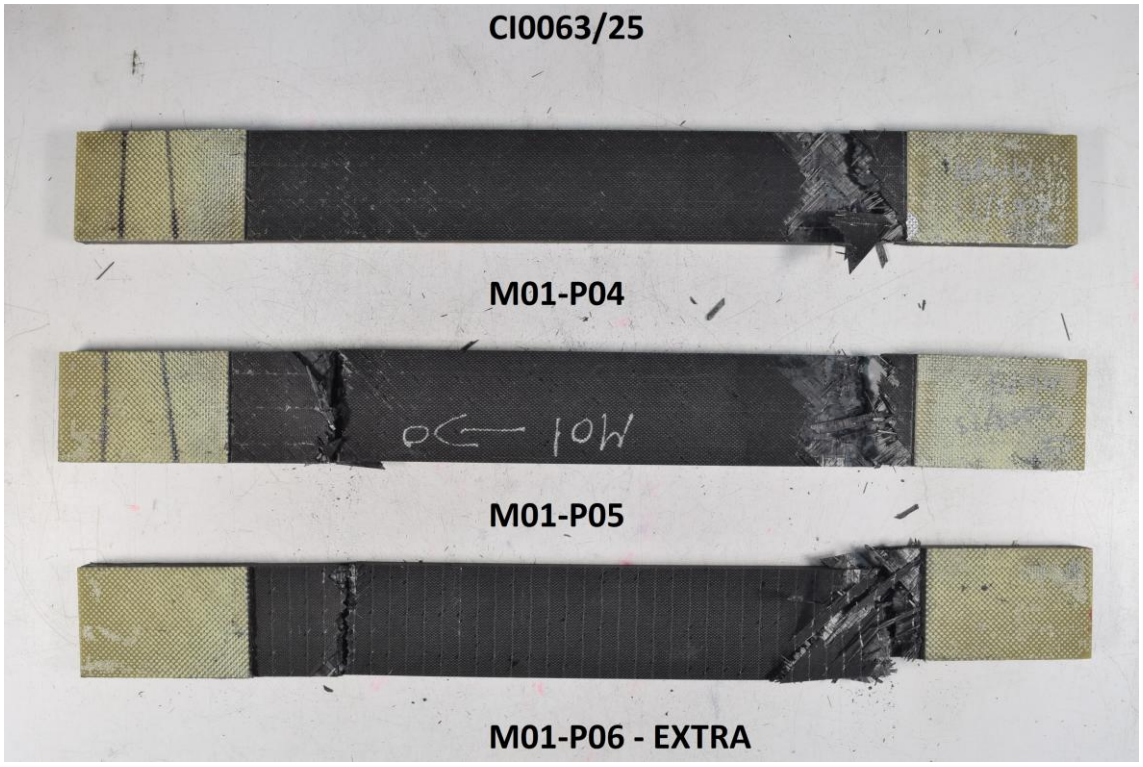

Figure 66. Failure mode for sensorised with microwires coupons – Batch 3. Tensile tests (plain), WET/RT.

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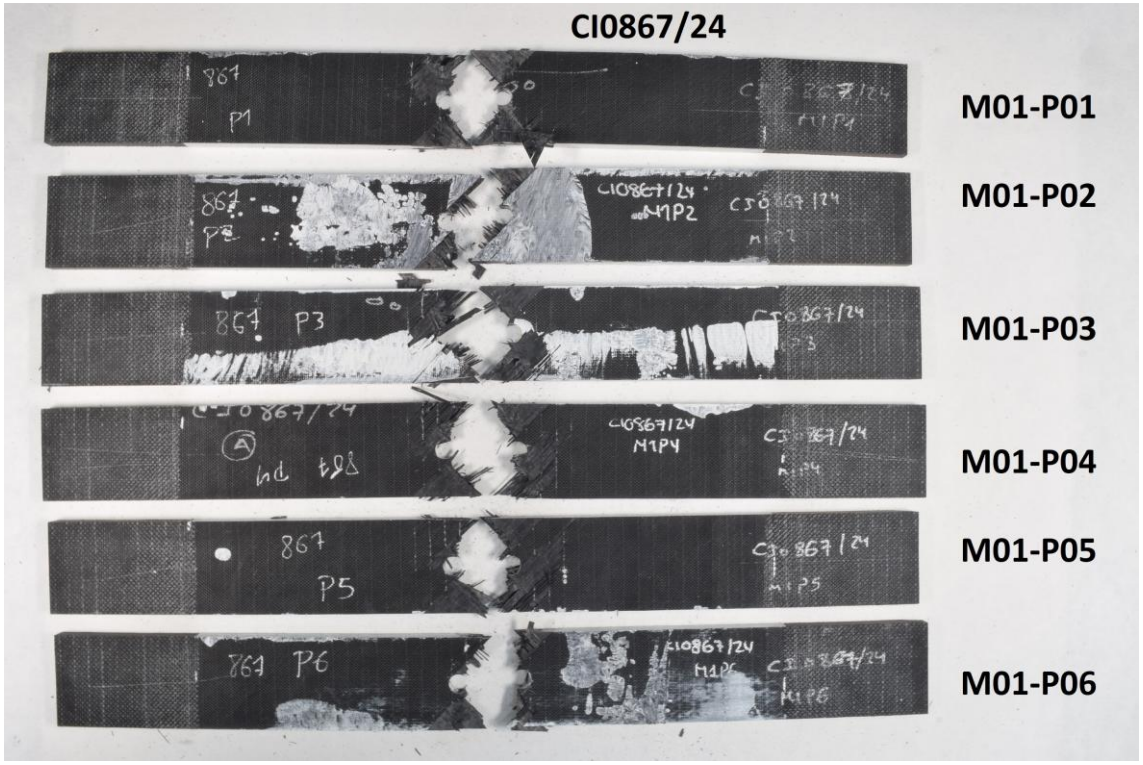

Figure 67. Failure mode for reference coupons – Batch 1. Tensile tests (OHT), RT.

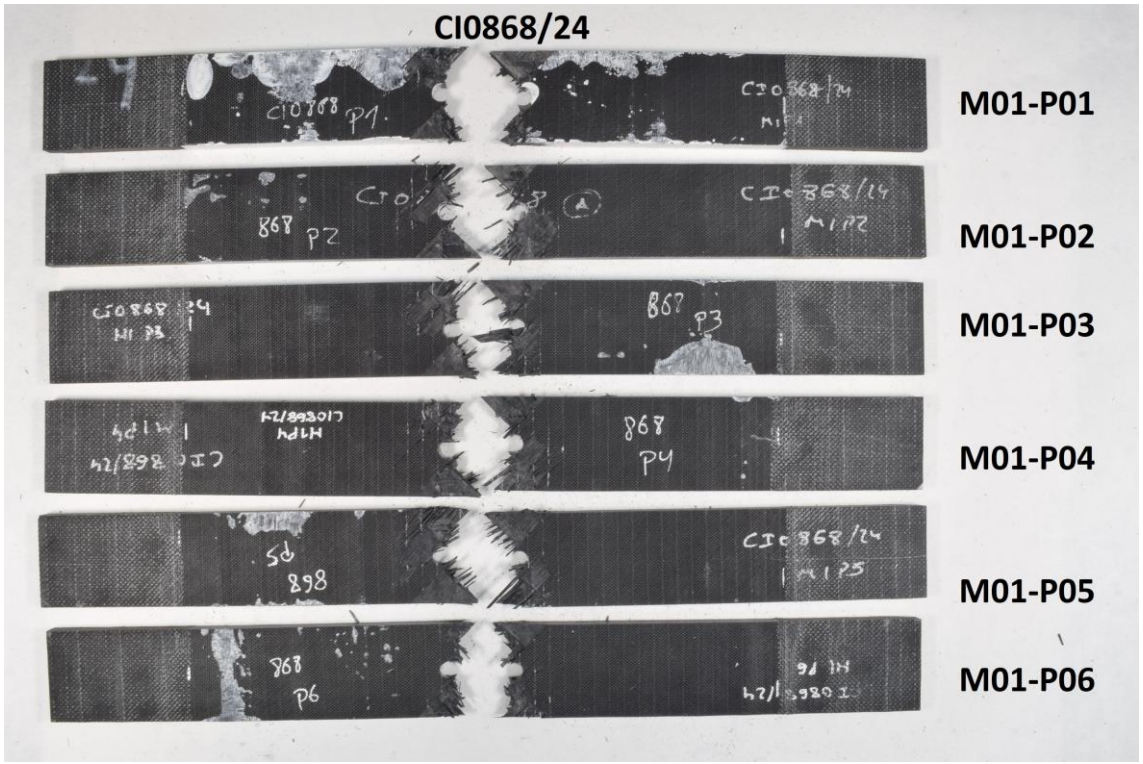

Figure 68. Failure mode for reference coupons – Batch 2. Tensile tests (OHT), RT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

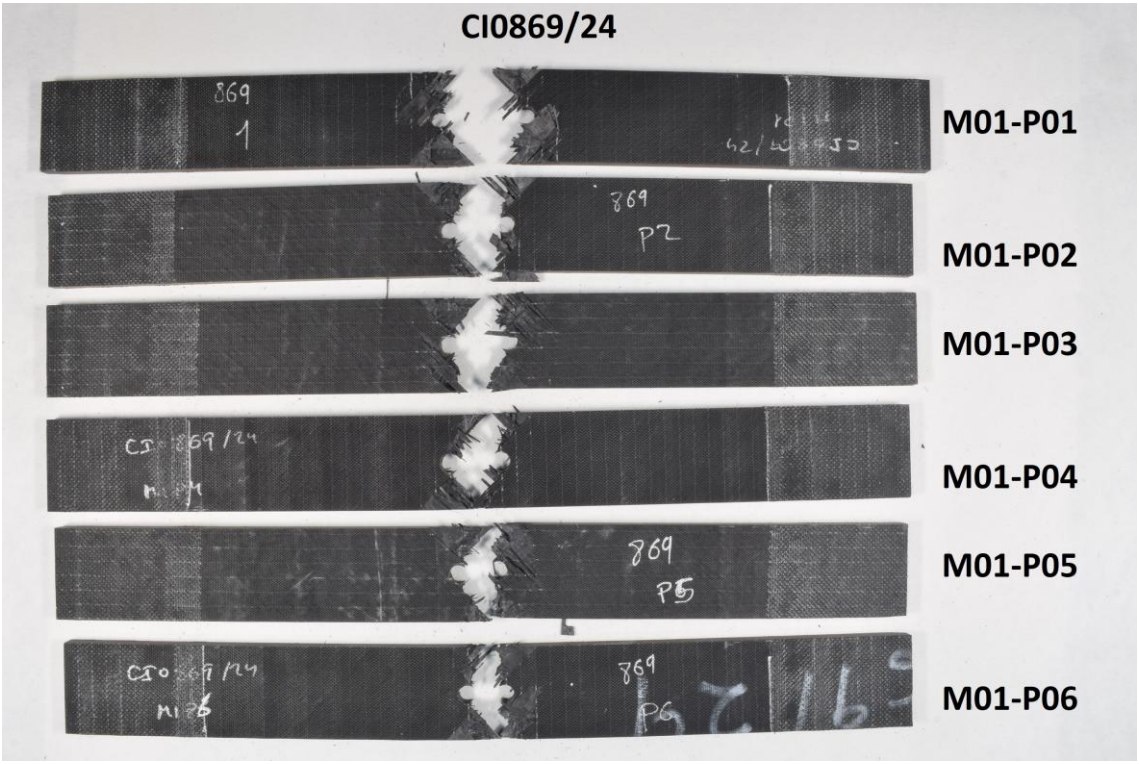

Figure 69. Failure mode for reference coupons – Batch 3. Tensile tests (OHT), RT.

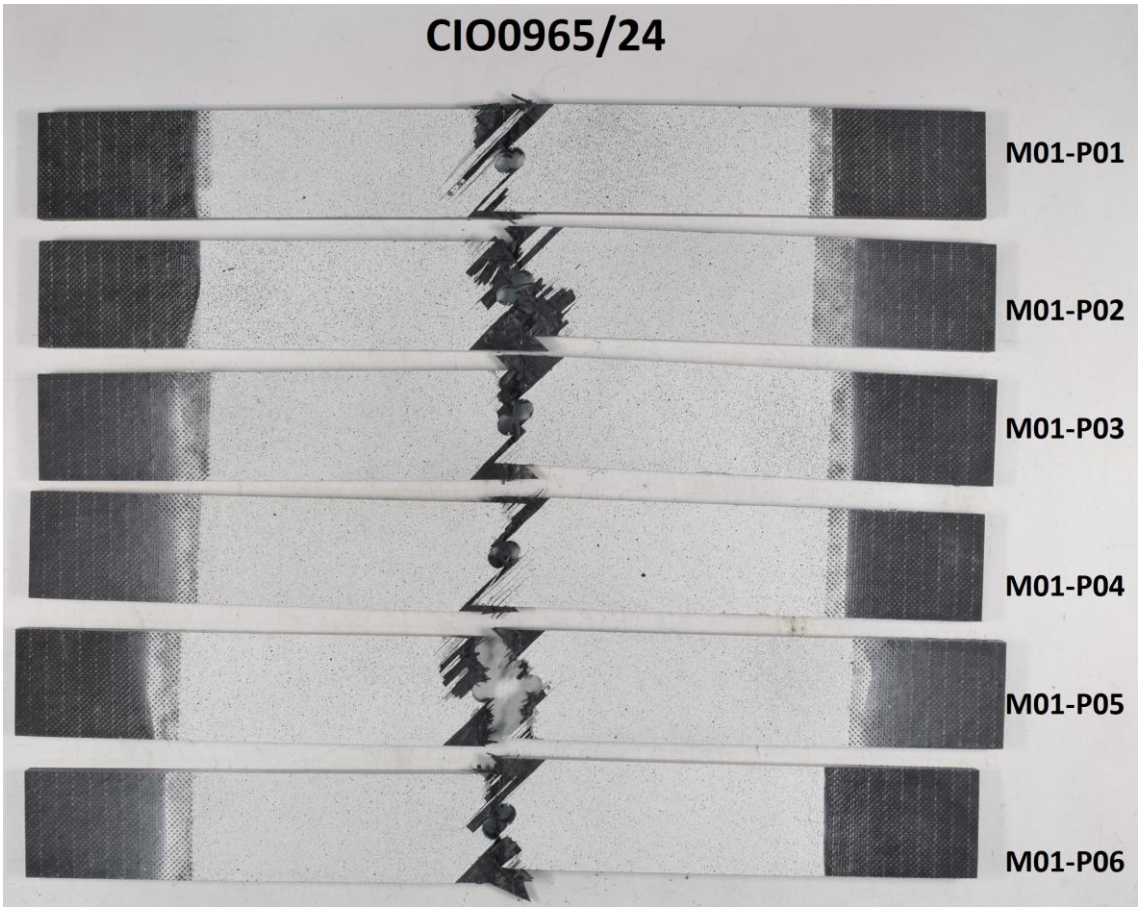

Figure 70. Failure mode for sensorised with microwires coupons – Batch 1. Tensile tests (OHT), RT.

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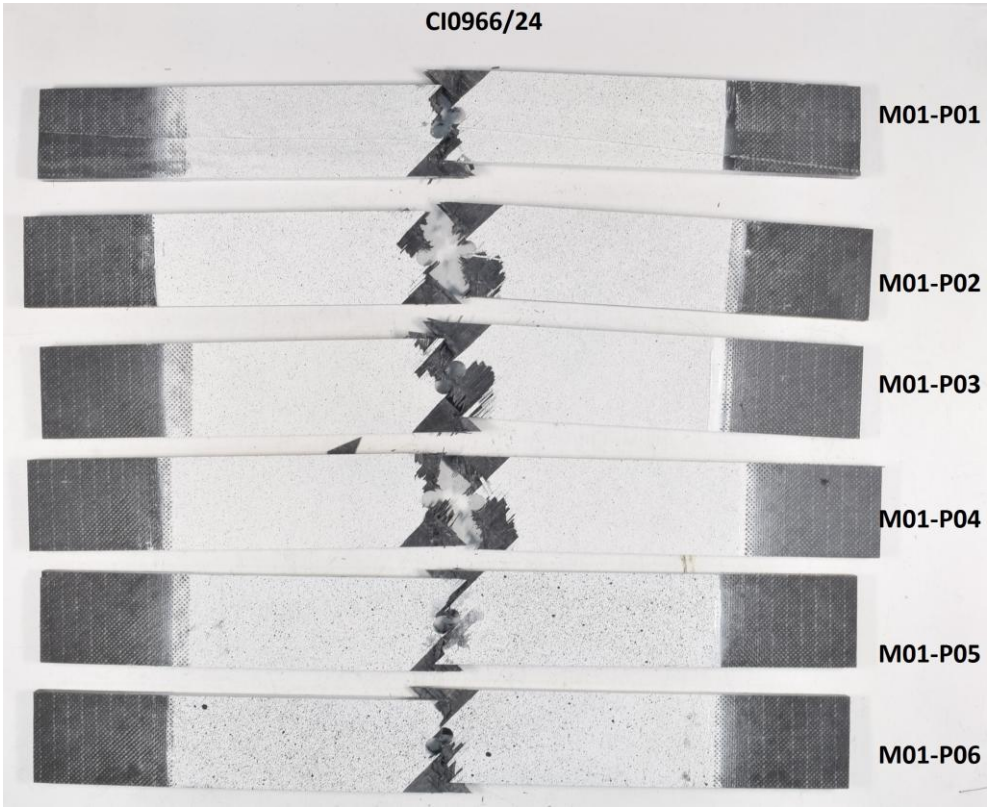

Figure 71. Failure mode for sensorised with microwires coupons – Batch 2. Tensile tests (OHT), RT.

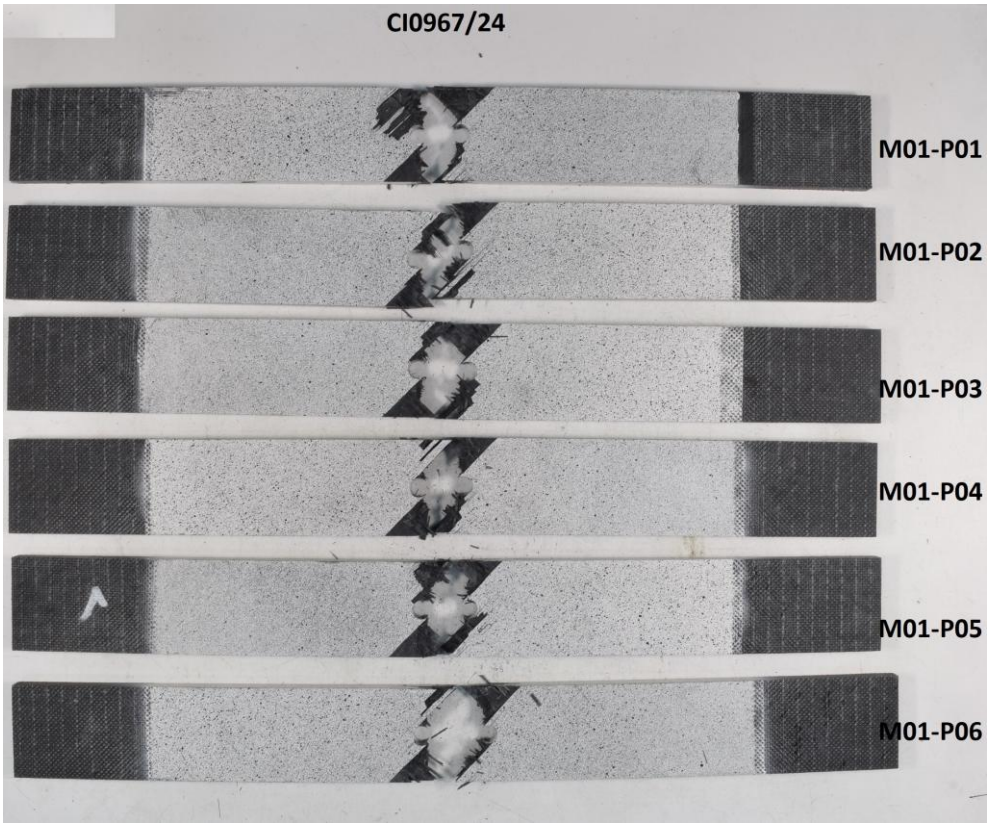

Figure 72. Failure mode for sensorised with microwires coupons – Batch 3. Tensile tests (OHT), RT.

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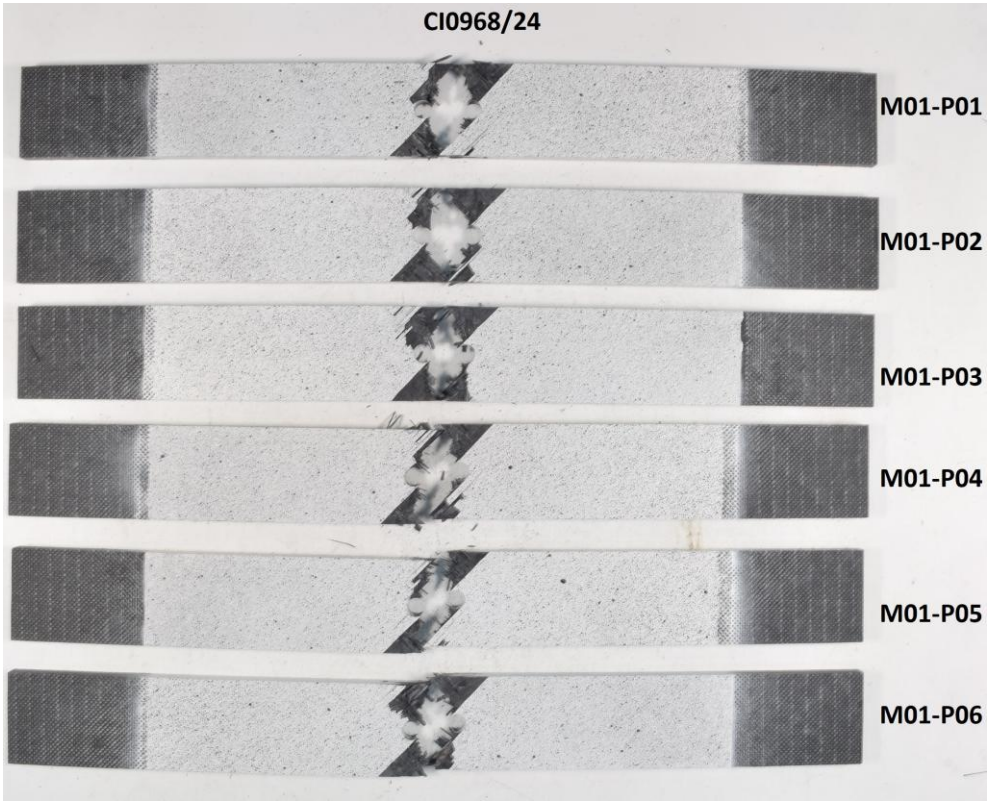

Figure 73. Failure mode for sensorised with microwires coupons – Batch 4. Tensile tests (OHT), RT.

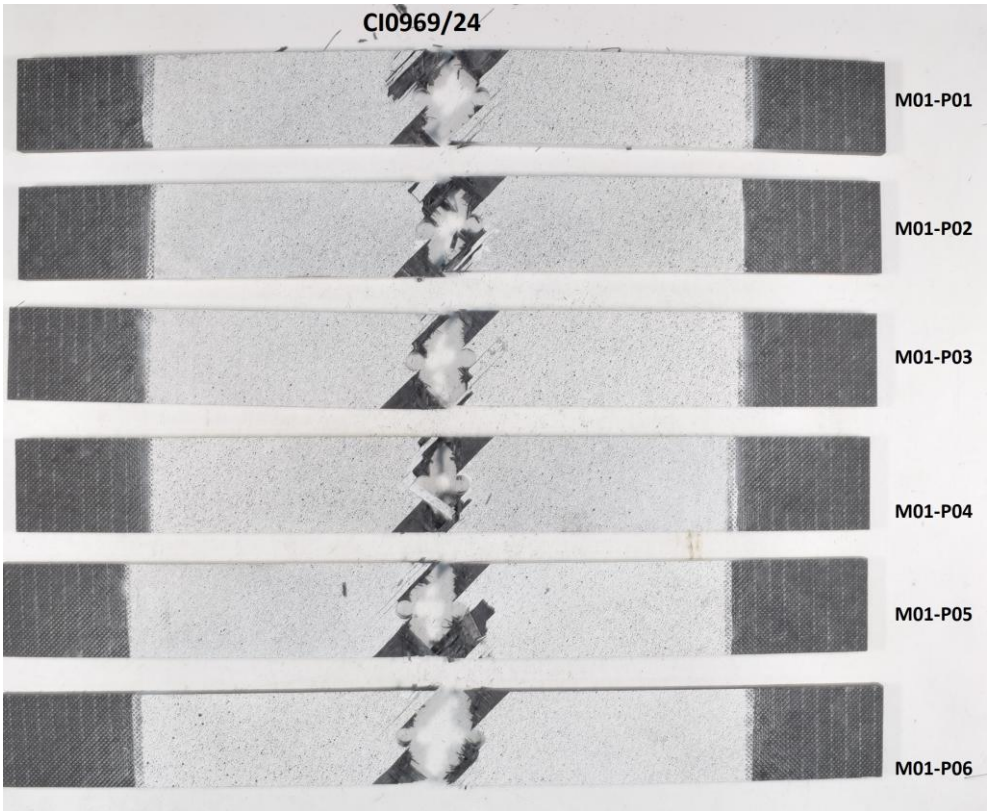

Figure 74. Failure mode for sensorised with microwires coupons – Batch 5. Tensile tests (OHT), RT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

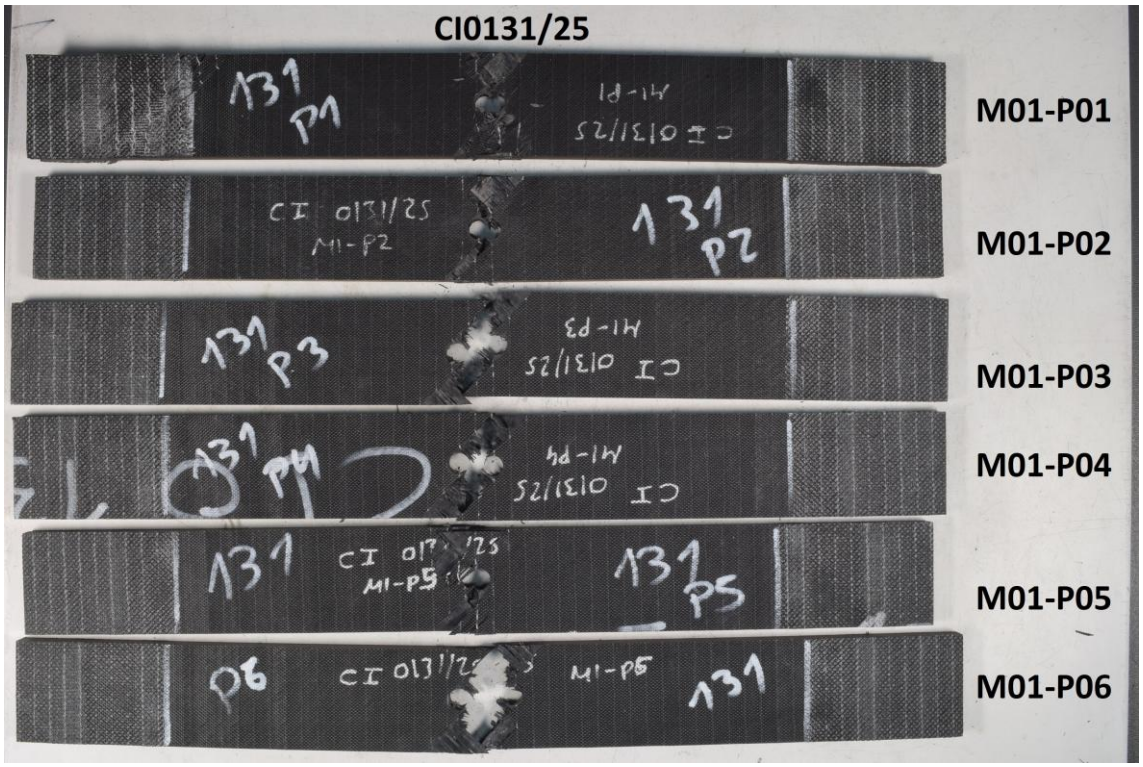

Figure 75. Failure mode for reference coupons – Batch 1. Tensile tests (OHT), HT.

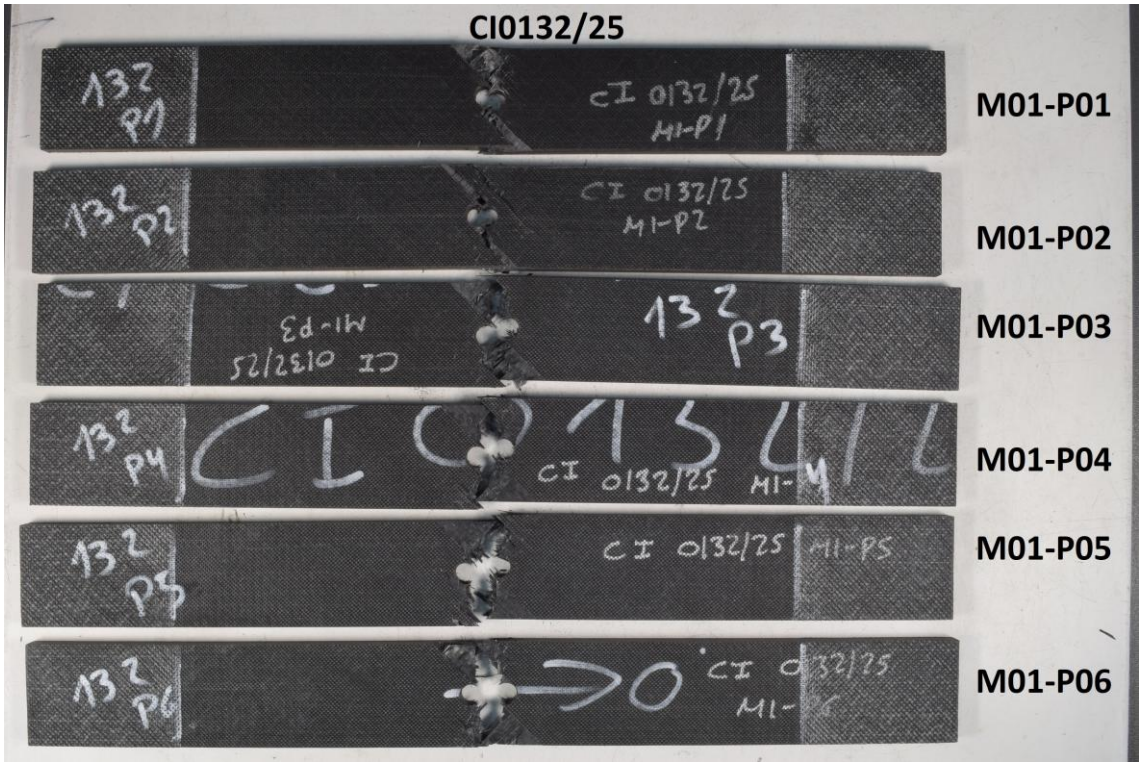

Figure 76. Failure mode for sensorised with microwires coupons – Batch 1. Tensile tests (OHT), HT.

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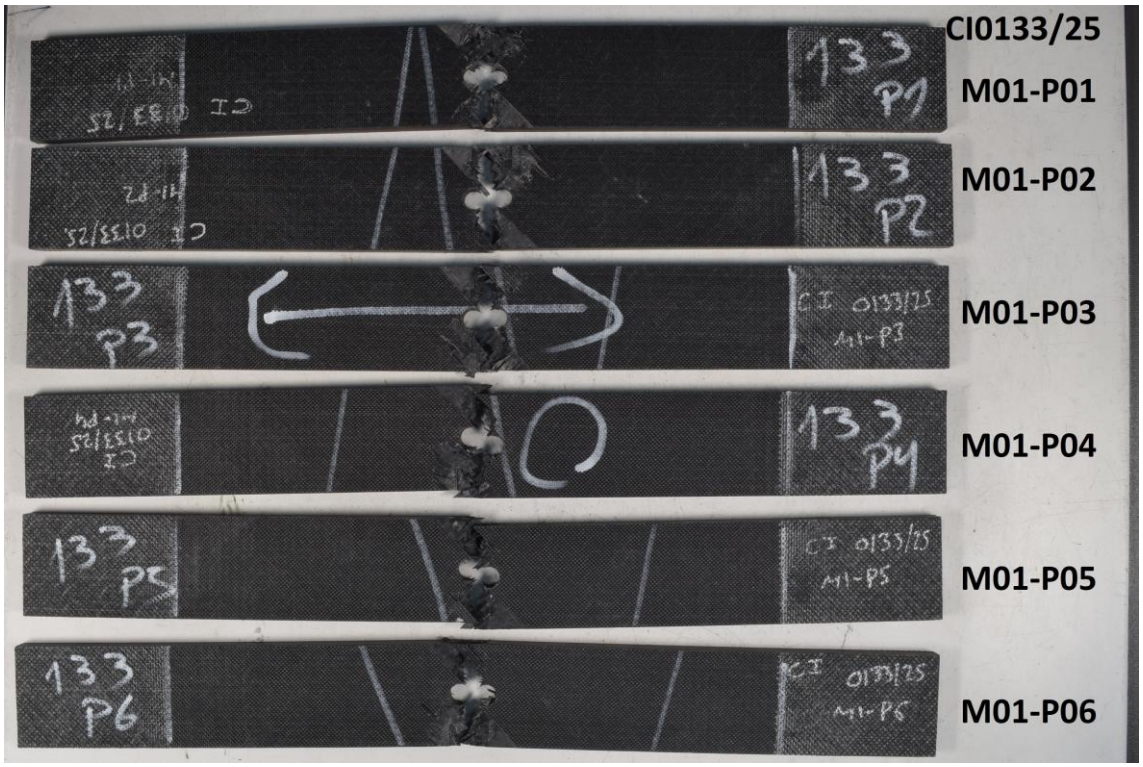

Figure 77. Failure mode for sensorised with microwires coupons – Batch 2. Tensile tests (OHT), HT.

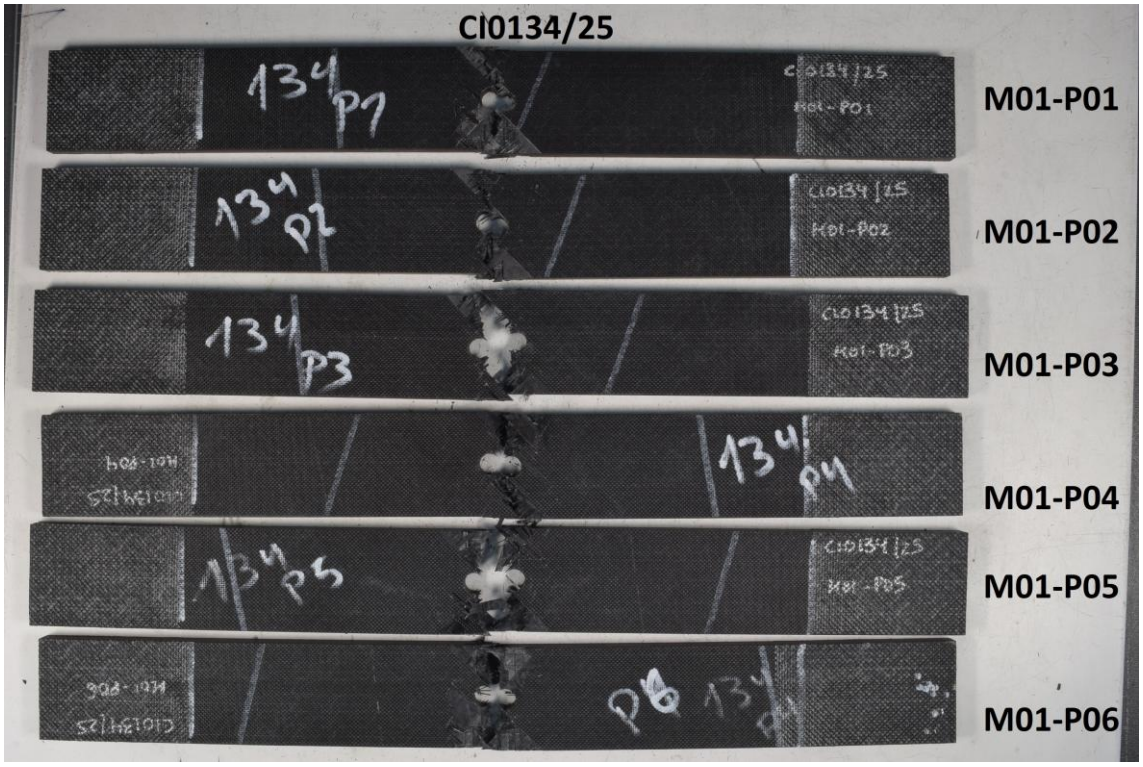

Figure 78. Failure mode for sensorised with microwires coupons – Batch 3. Tensile tests (OHT), HT.

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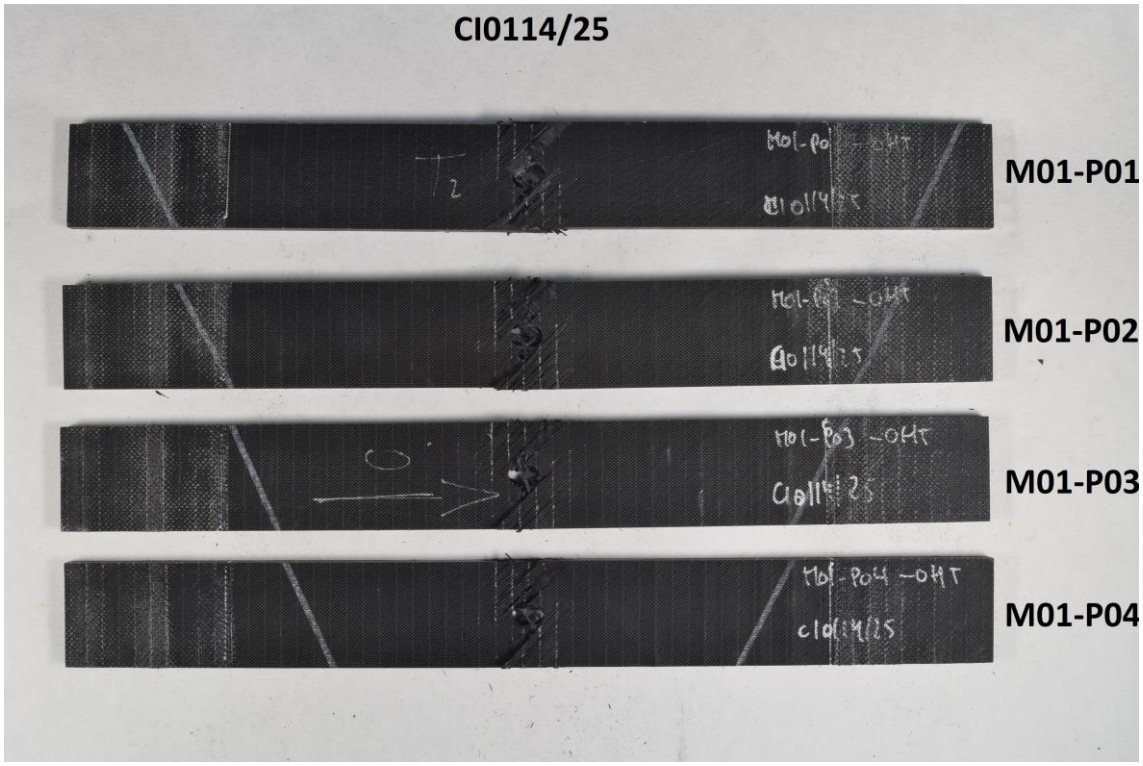

Figure 79. Failure mode for reference coupons – Batch 1. Tensile tests (OHT), LT.

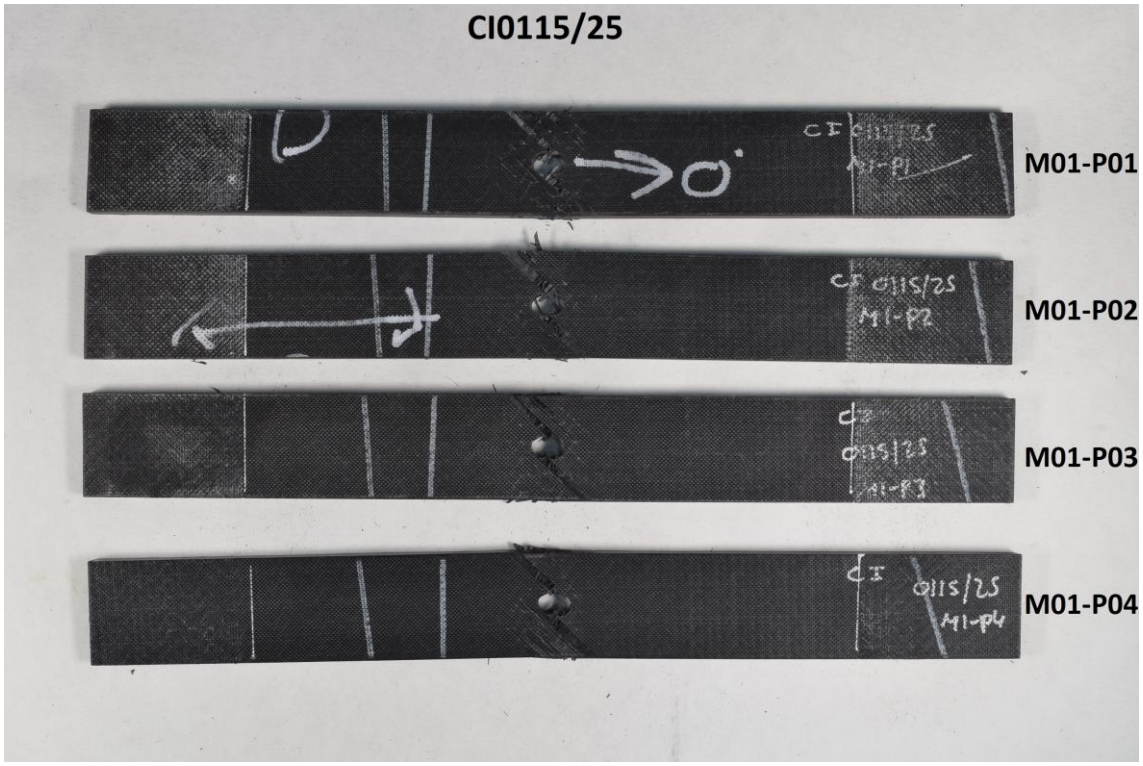

Figure 80. Failure mode for sensorised with microwires coupons – Batch 1. Tensile tests (OHT), LT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

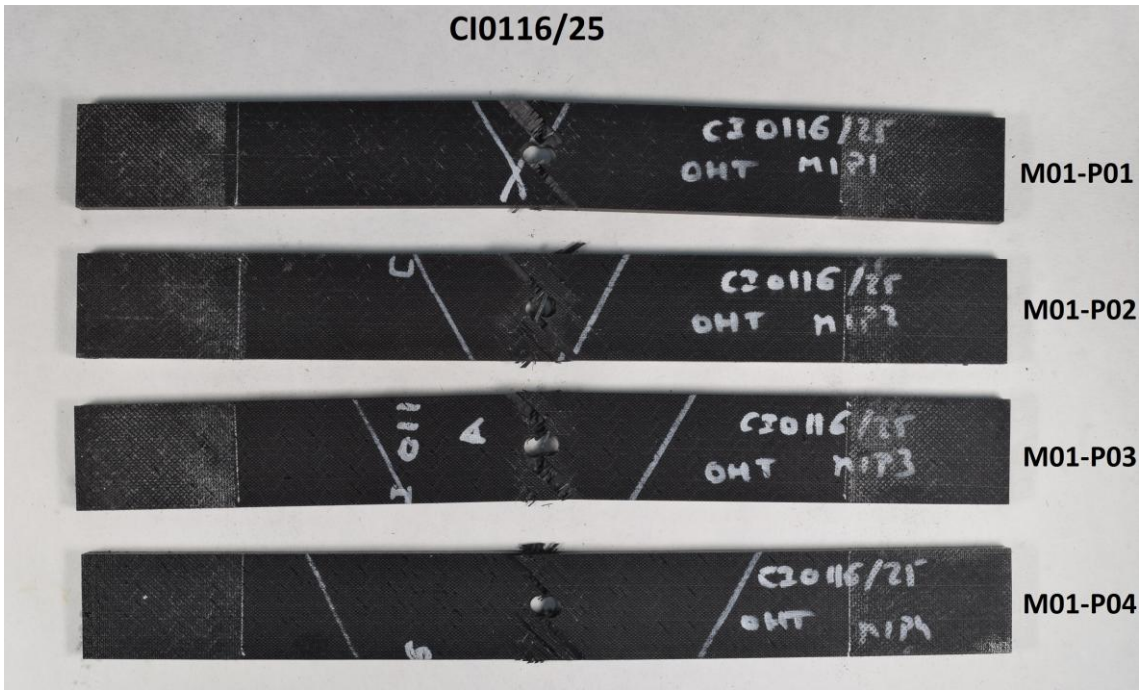

Figure 81. Failure mode for sensorised with microwires coupons – Batch 2. Tensile tests (OHT), LT.

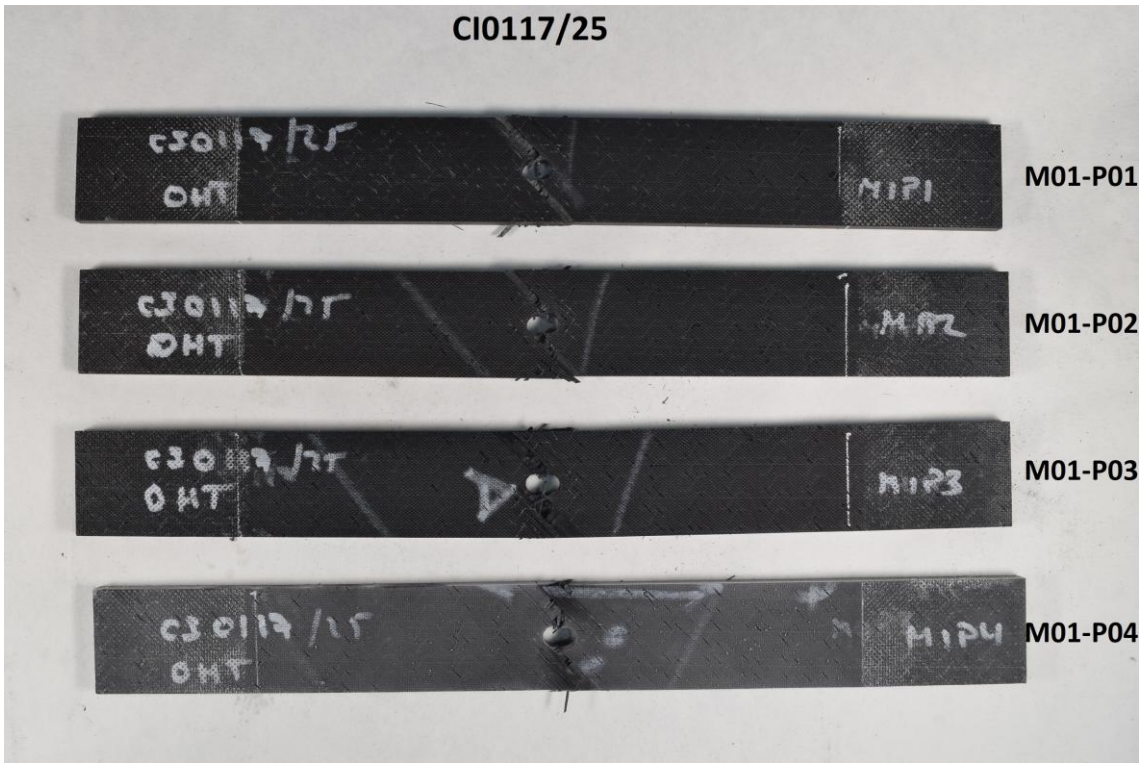

Figure 82. Failure mode for sensorised with microwires coupons – Batch 3. Tensile tests (OHT), LT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

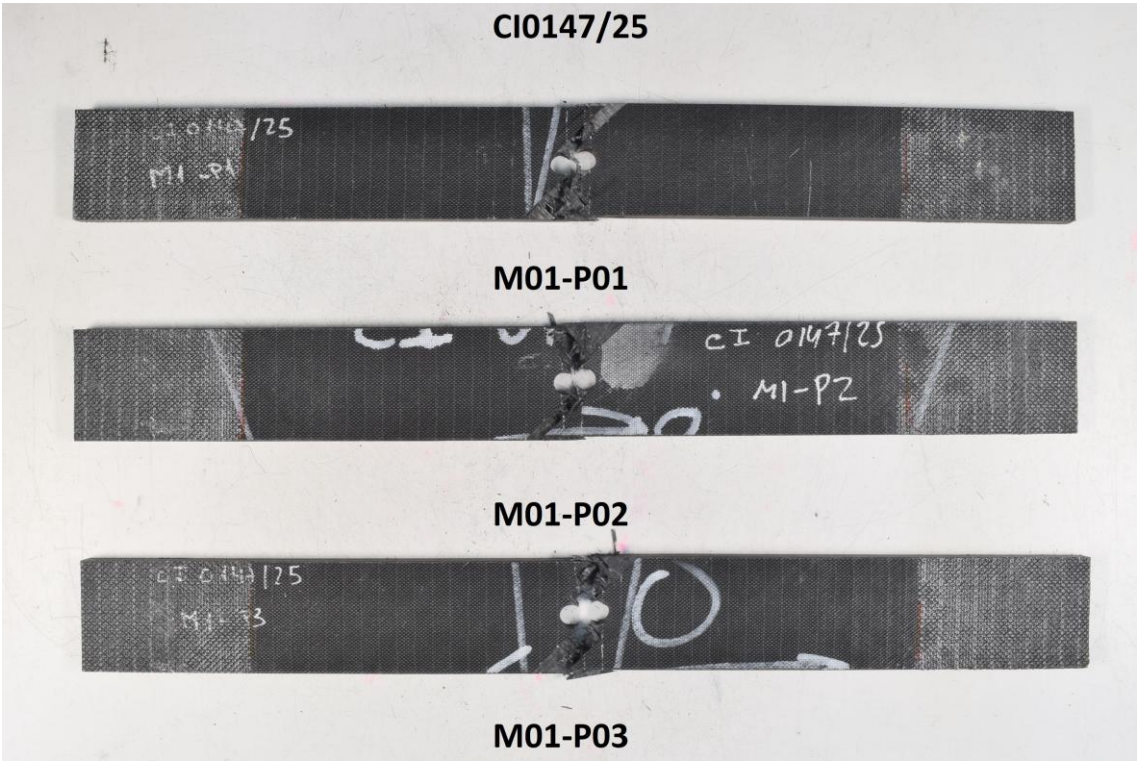

Figure 83. Failure mode for reference coupons – Batch 1. Tensile tests (OHT), WET/RT.

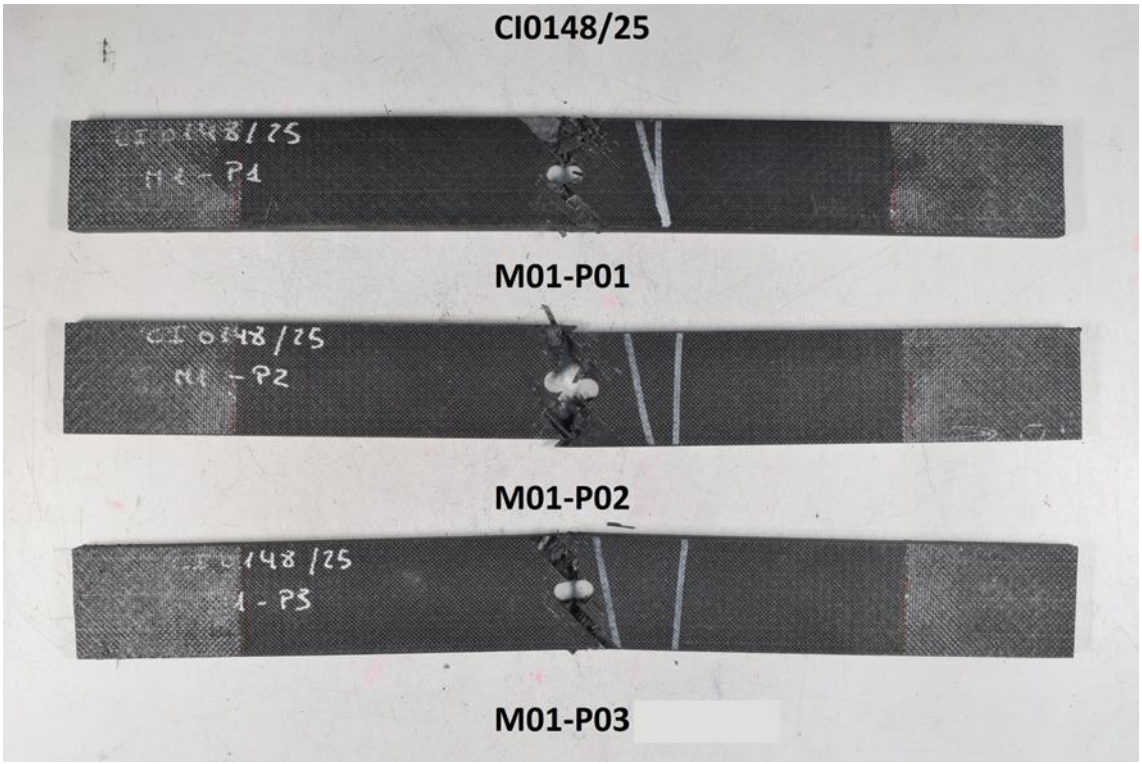

Figure 84. Failure mode for sensorised with microwires coupons – Batch 1. Tensile tests (OHT), WET/RT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

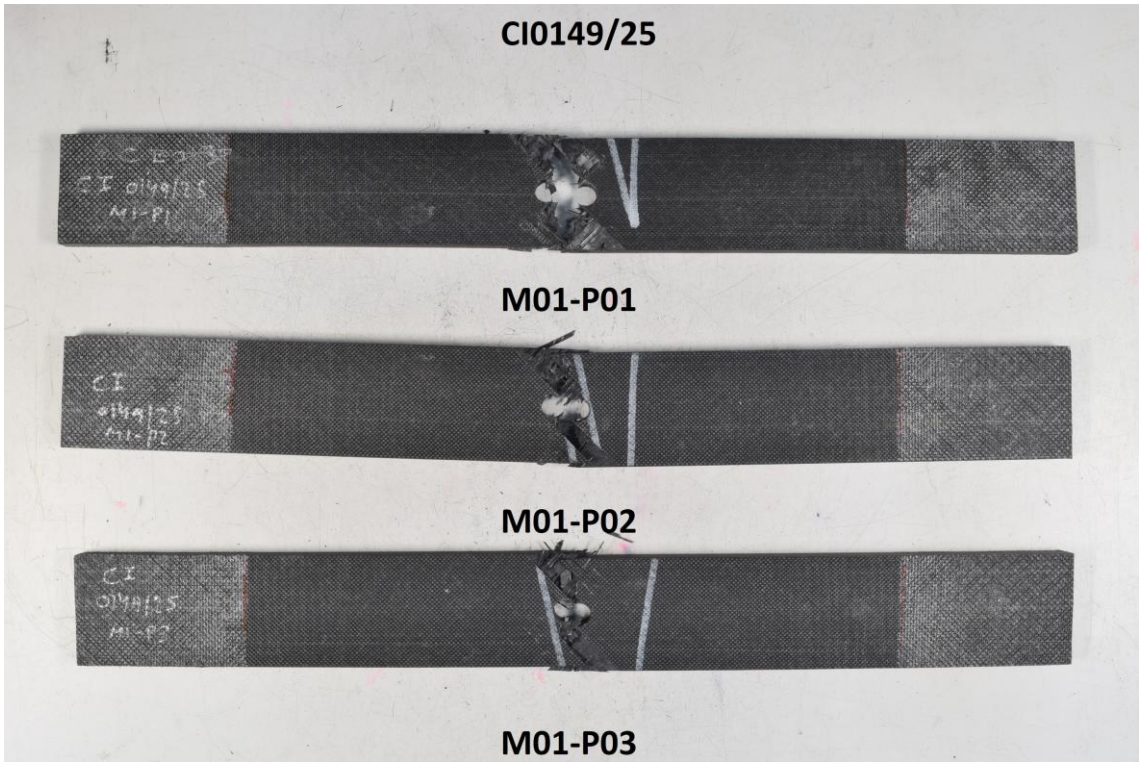

Figure 85. Failure mode for sensorised with microwires coupons – Batch 2. Tensile tests (OHT), WET/RT.

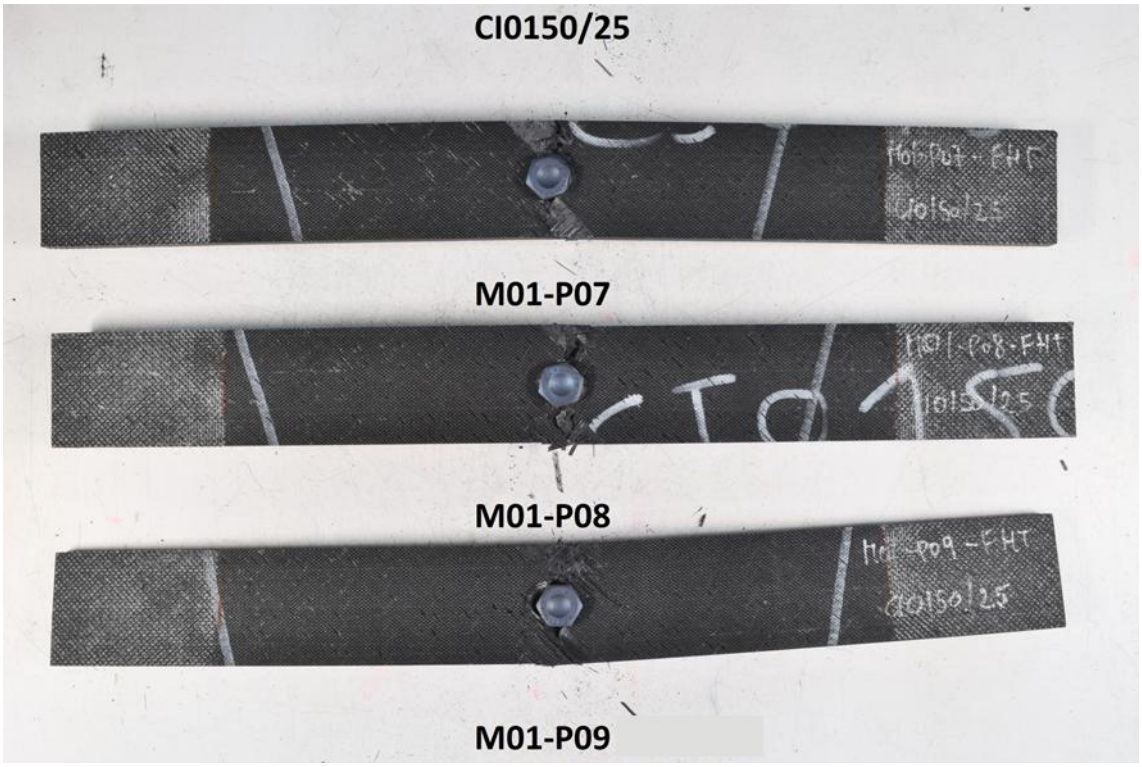

Figure 86. Failure mode for sensorised with microwires coupons – Batch 3. Tensile tests (OHT), WET/RT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

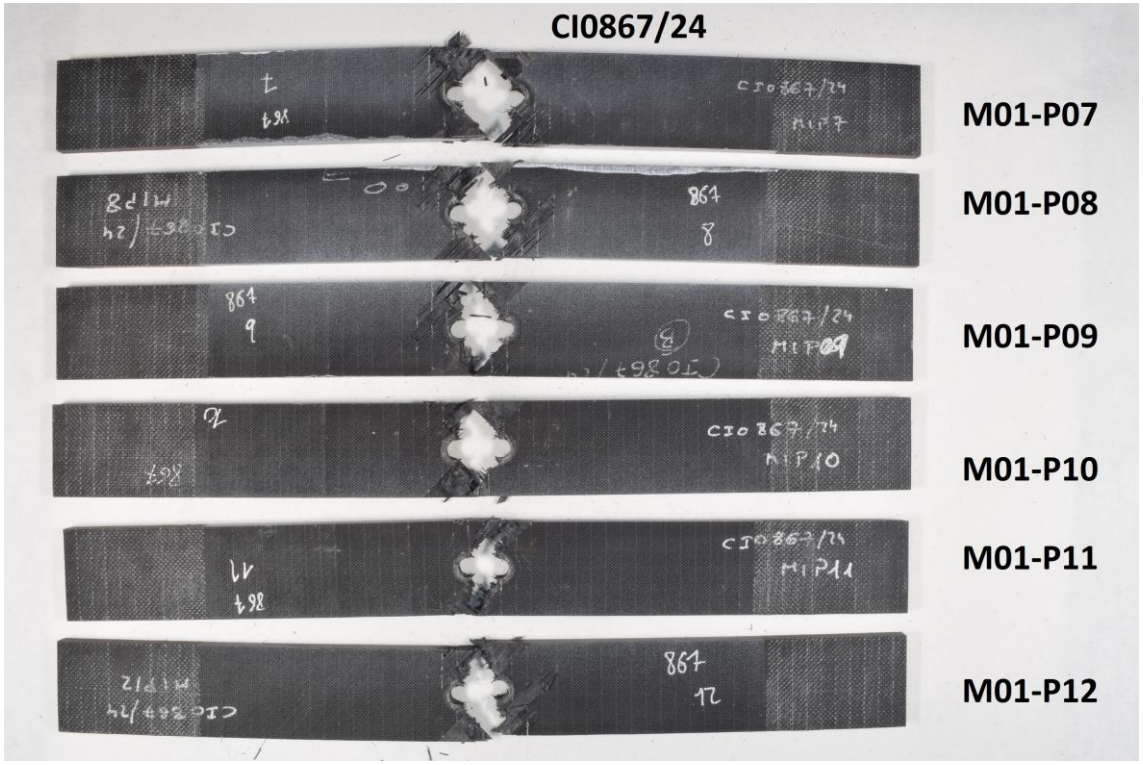

Figure 87. Failure mode for reference coupons – Batch 1. Tensile tests (FHT), RT.

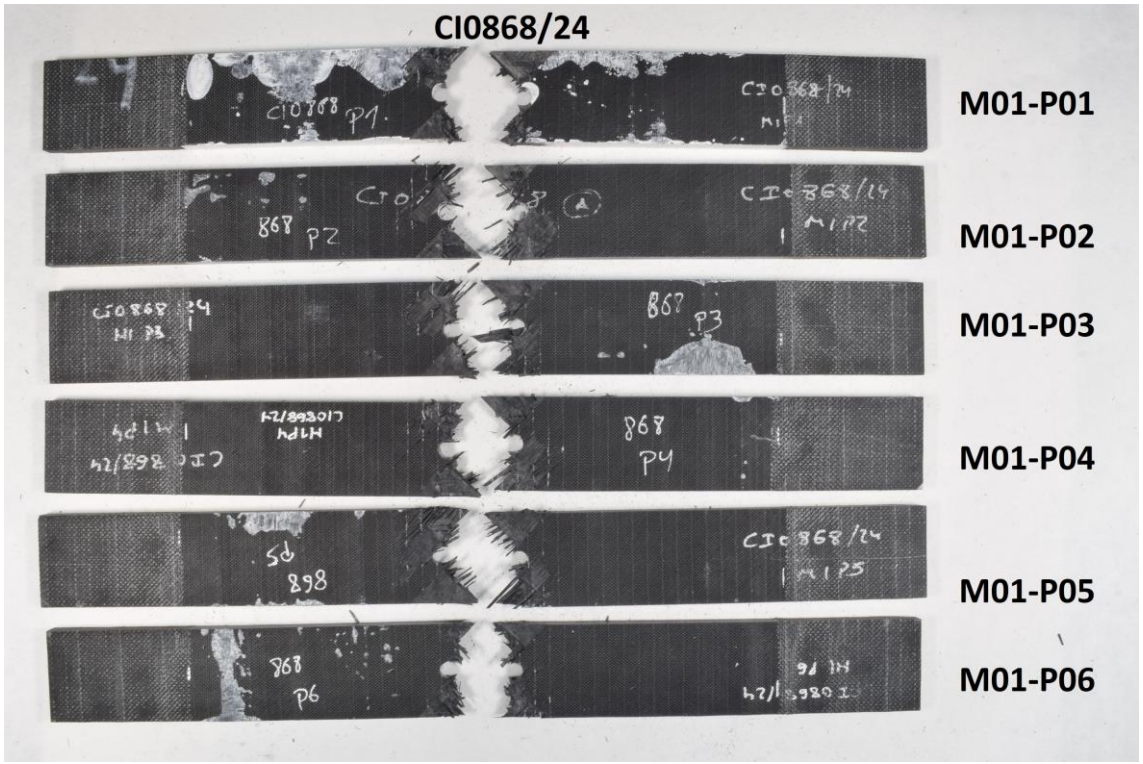

Figure 88. Failure mode for reference coupons – Batch 2. Tensile tests (FHT), RT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

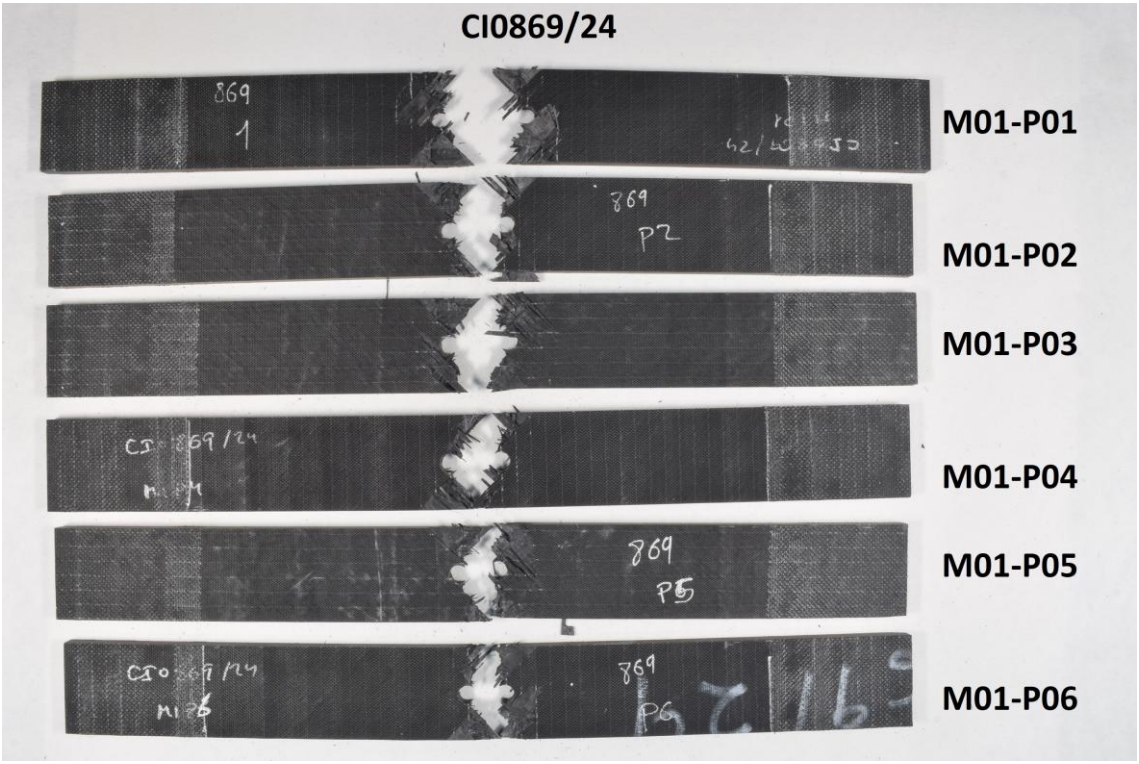

Figure 89. Failure mode for reference coupons – Batch 3. Tensile tests (FHT), RT.

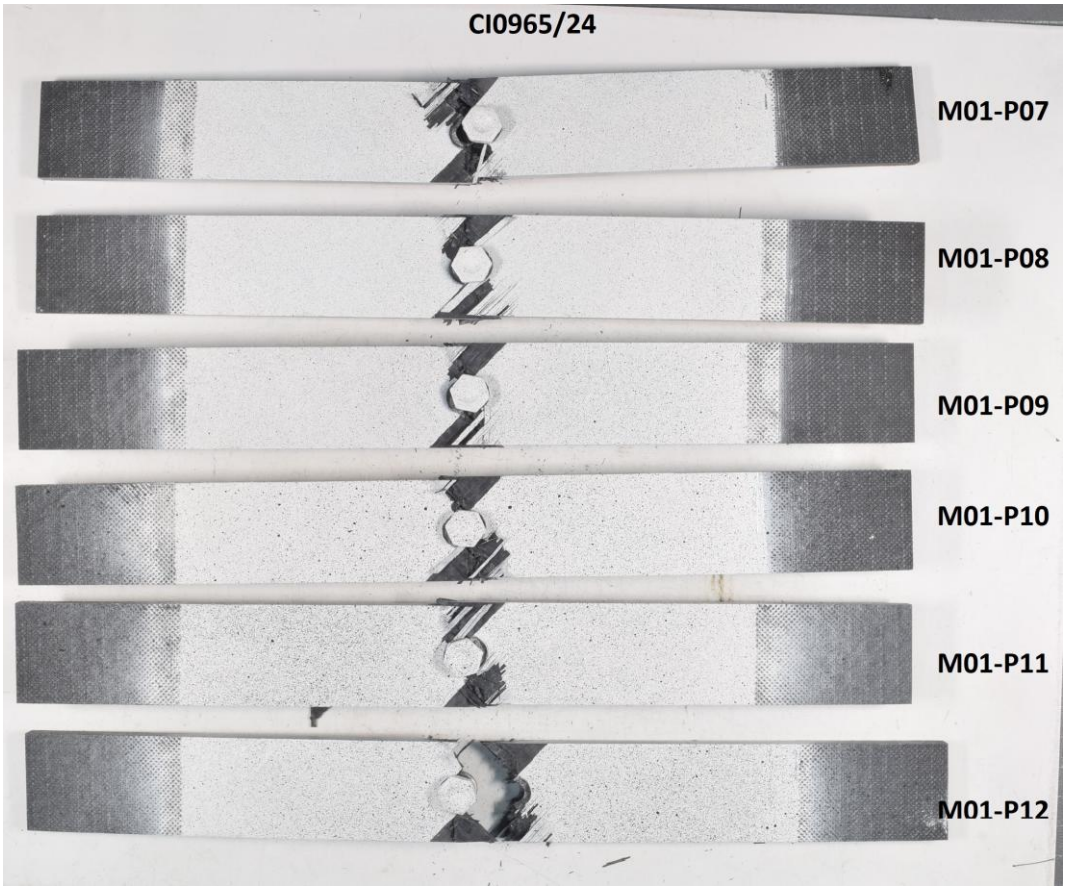

Figure 90. Failure mode for sensorised with microwires coupons – Batch 1. Tensile tests (FHT), RT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

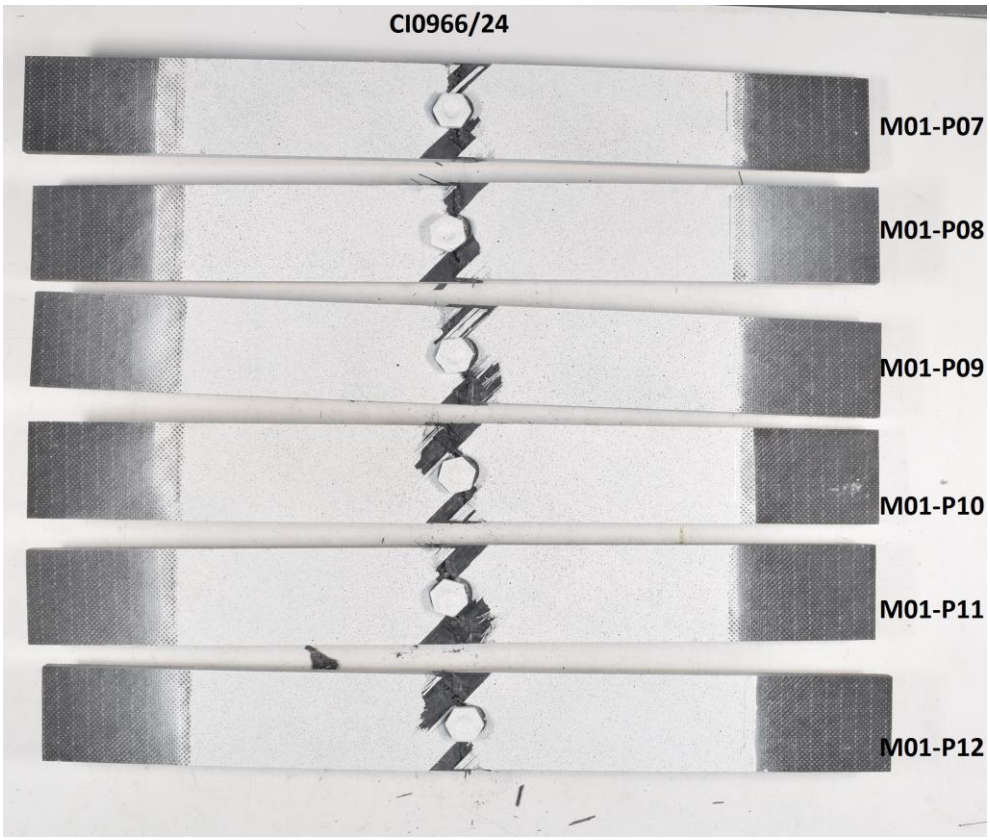

Figure 91. Failure mode for sensorised with microwires coupons – Batch 2. Tensile tests (FHT), RT.

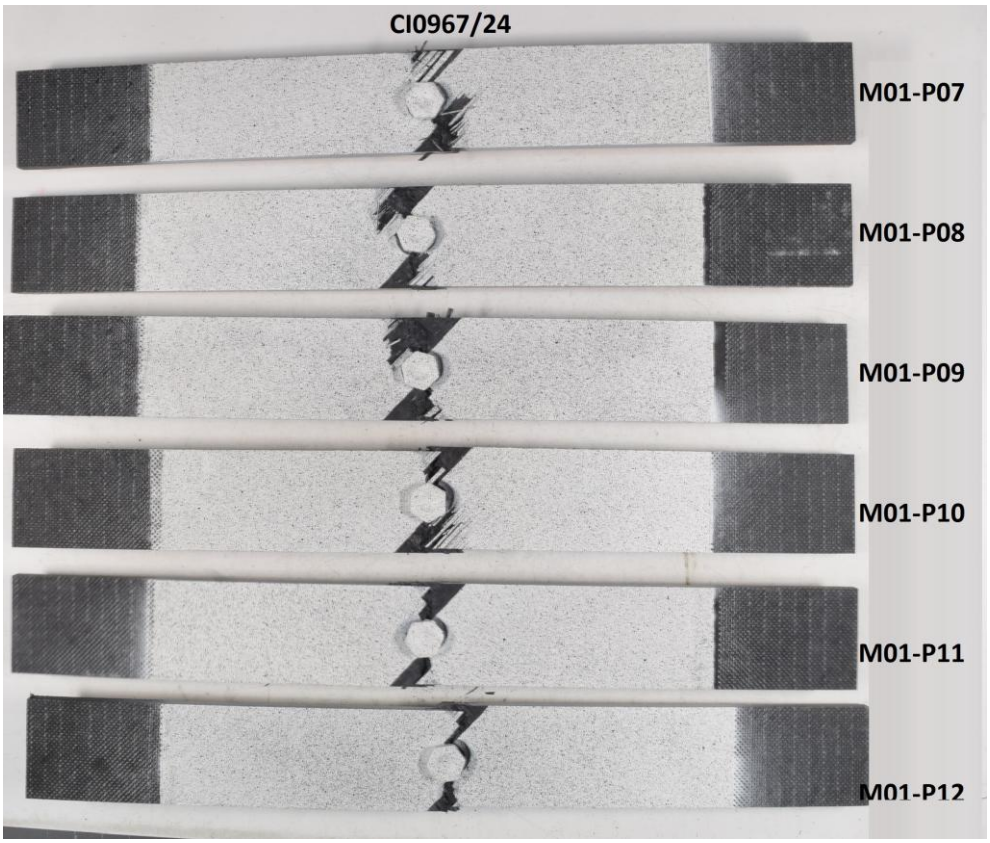

Figure 92. Failure mode for sensorised with microwires coupons – Batch 3. Tensile tests (FHT), RT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

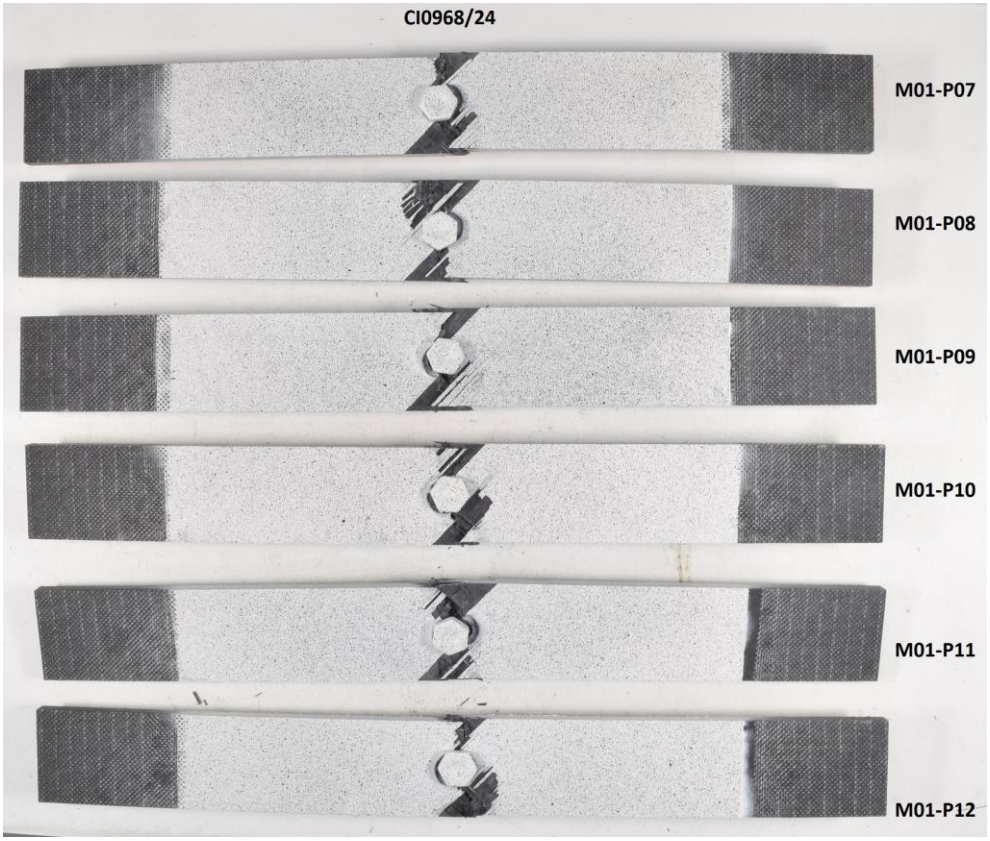

Figure 93. Failure mode for sensorised with microwires coupons – Batch 4. Tensile tests (FHT), RT.

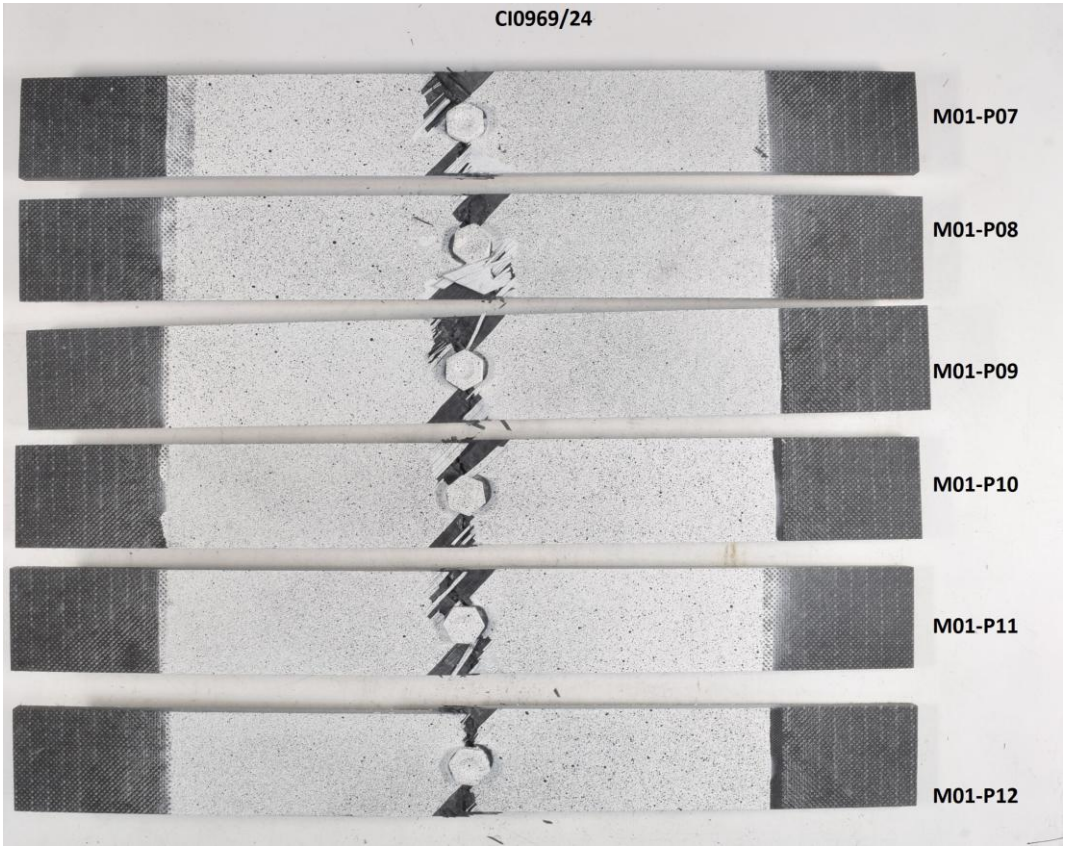

Figure 94. Failure mode for sensorised with microwires coupons – Batch 5. Tensile tests (FHT), RT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

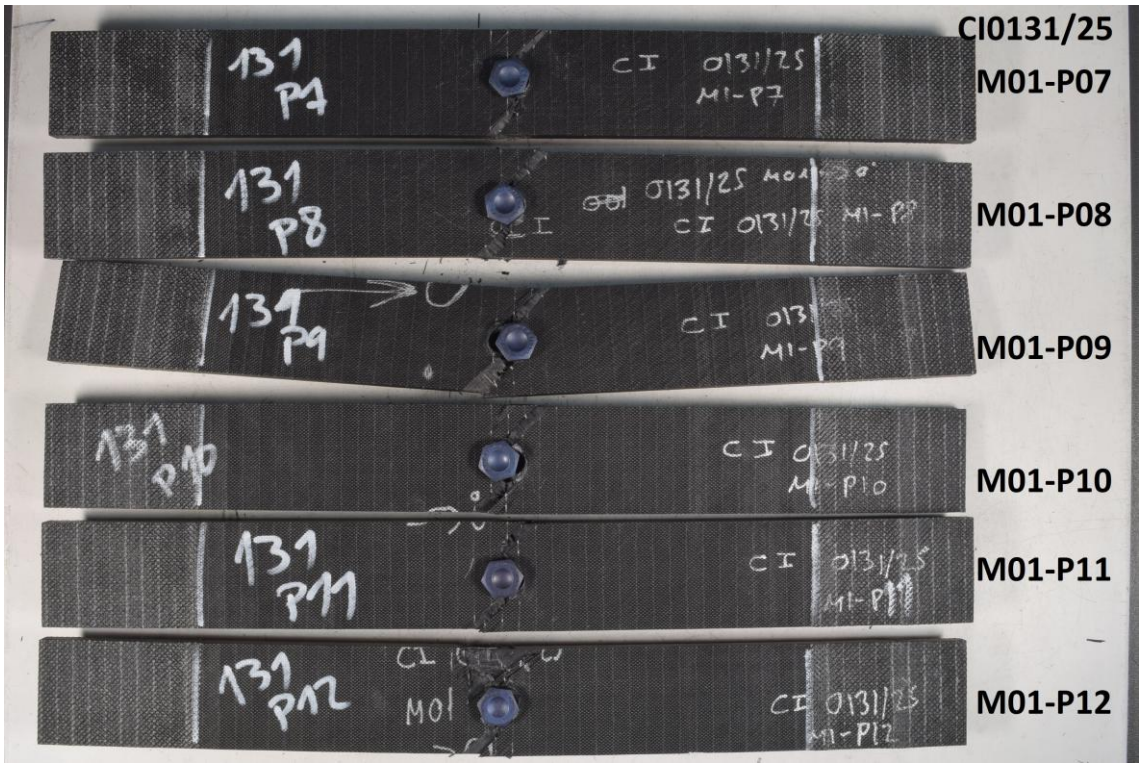

Figure 95. Failure mode for reference coupons – Batch 1. Tensile tests (FHT), HT.

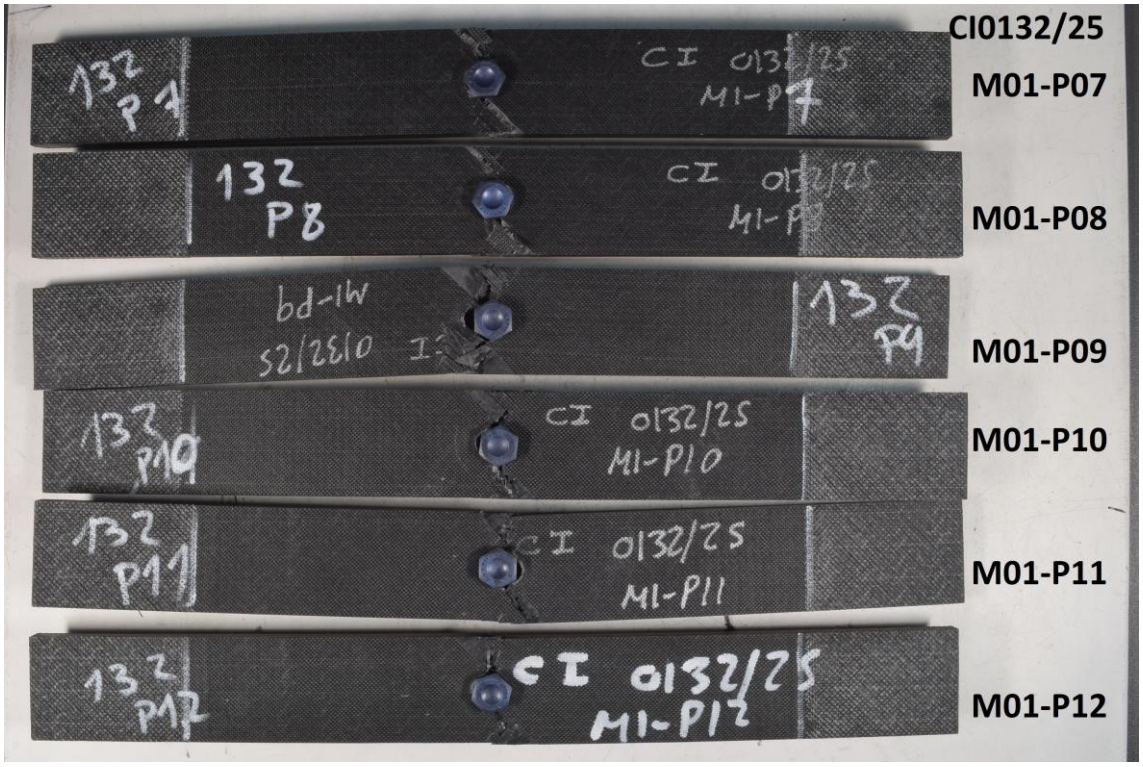

Figure 96. Failure mode for sensorised with microwires coupons – Batch 1. Tensile tests (FHT), HT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

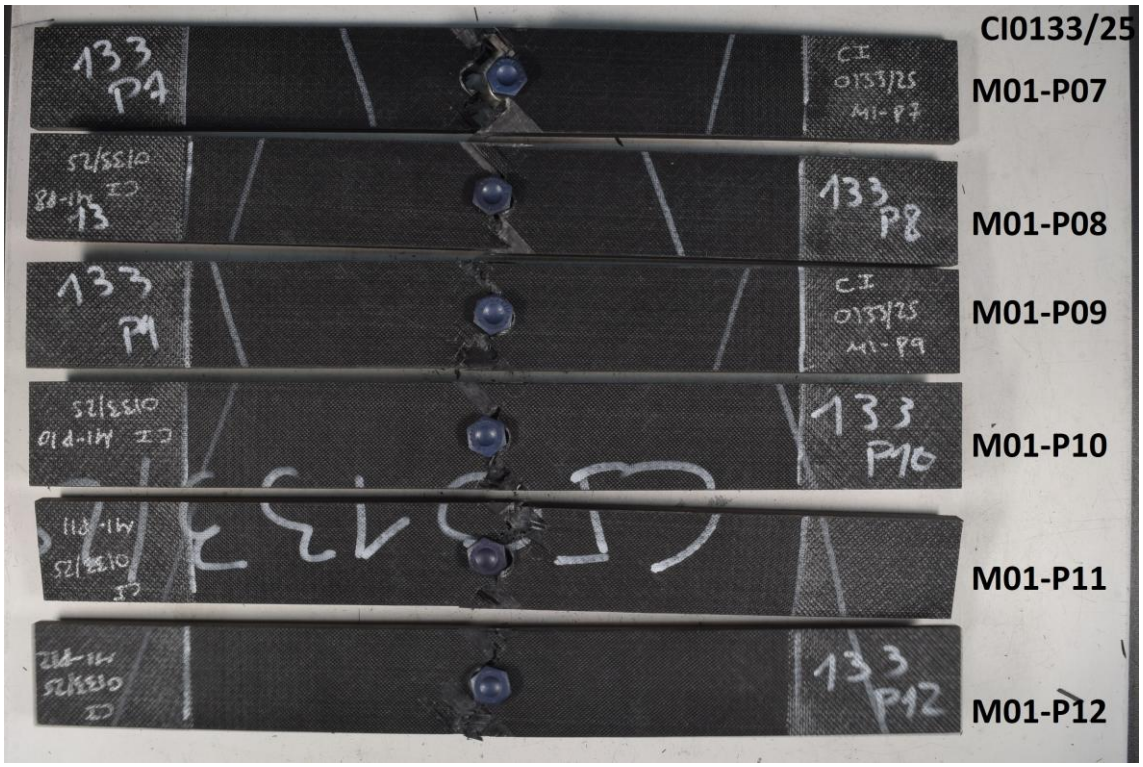

Figure 97. Failure mode for sensorised with microwires coupons – Batch 2. Tensile tests (FHT), HT.

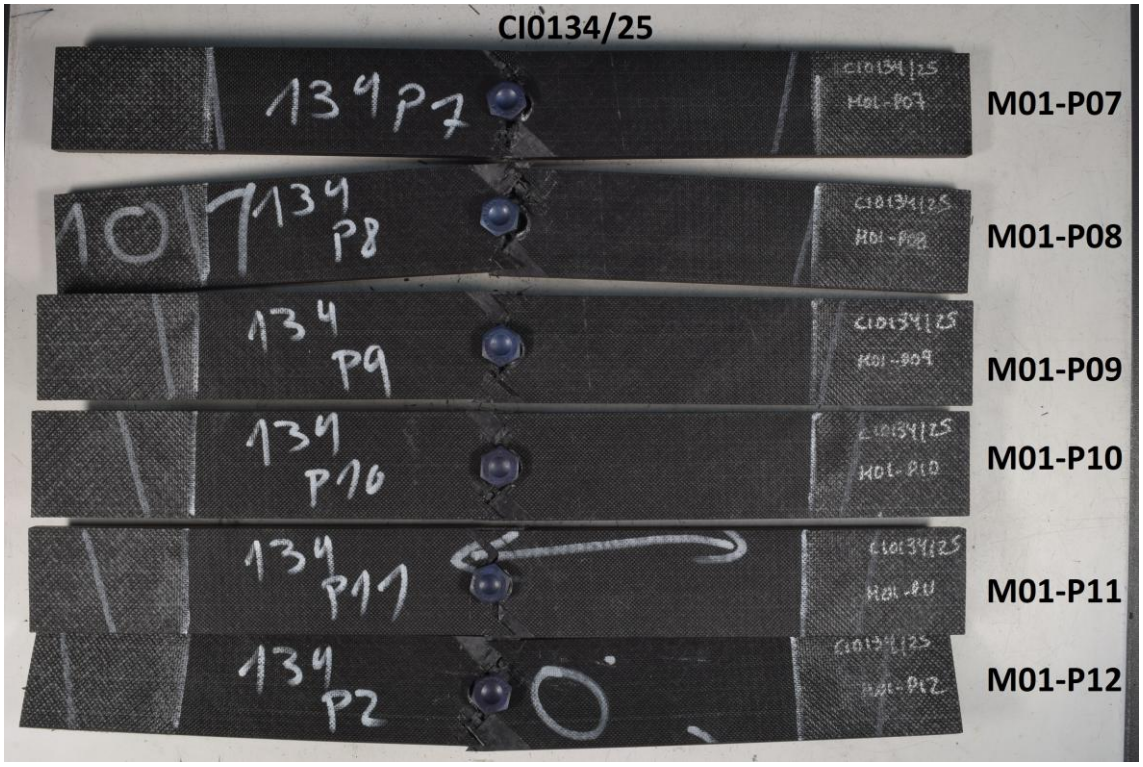

Figure 98. Failure mode for sensorised with microwires coupons – Batch 3. Tensile tests (FHT), HT.

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Figure 99. Failure mode for reference coupons – Batch 1. Tensile tests (FHT), LT.

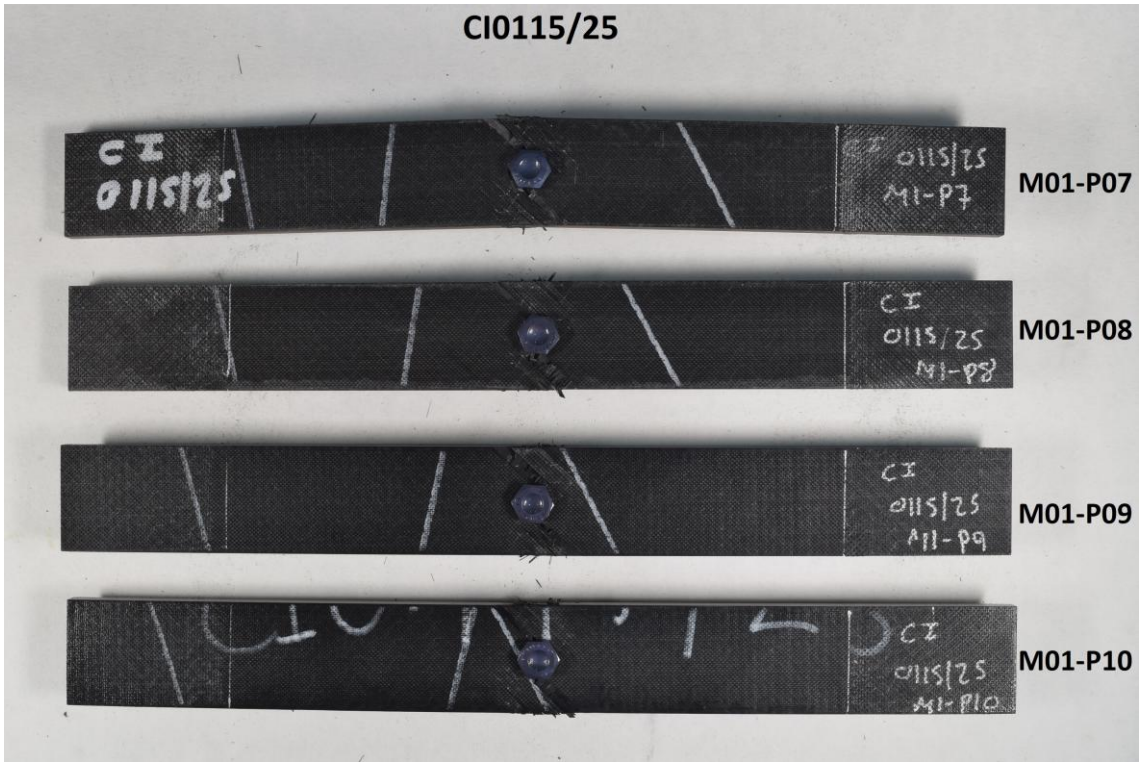

Figure 100. Failure mode for sensorised with microwires coupons – Batch 1. Tensile tests (FHT), LT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

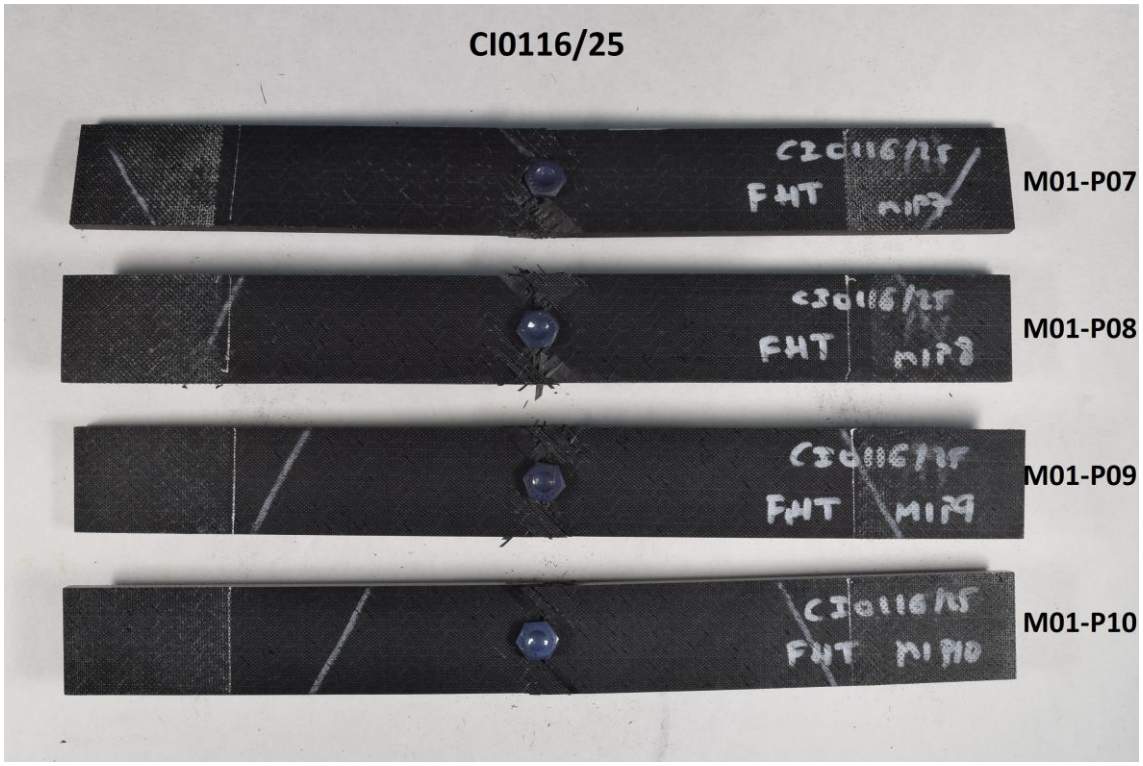

Figure 101. Failure mode for sensorised with microwires coupons – Batch 2. Tensile tests (FHT), LT.

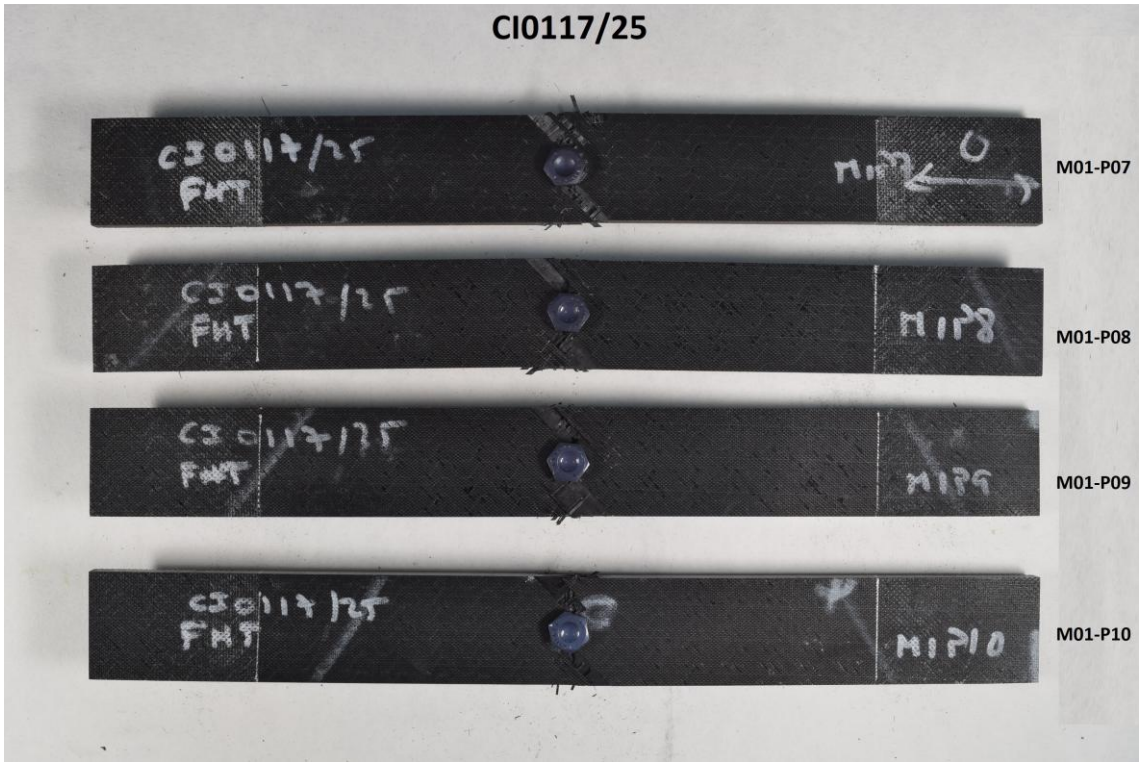

Figure 102. Failure mode for sensorised with microwires coupons – Batch 3. Tensile tests (FHT), LT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

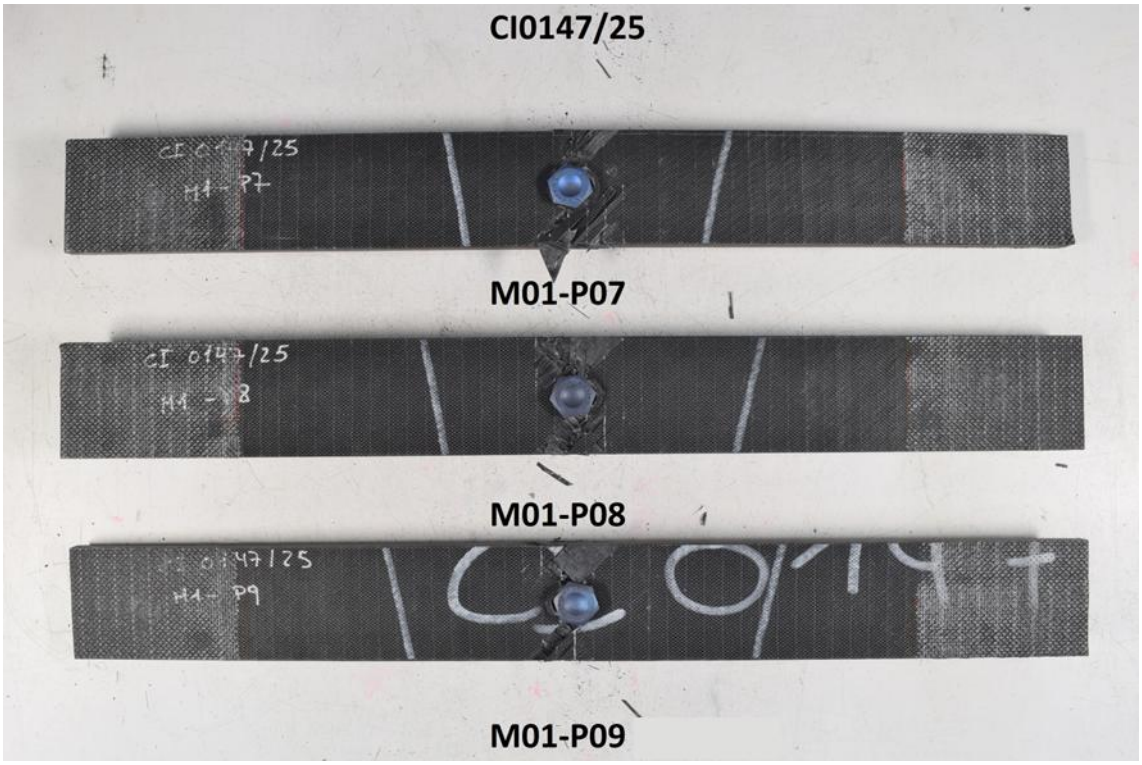

Figure 103. Failure mode for reference coupons – Batch 1. Tensile tests (FHT), WET/RT.

Figure 104. Failure mode for sensorised with microwires coupons – Batch 1. Tensile tests (FHT), WET/RT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

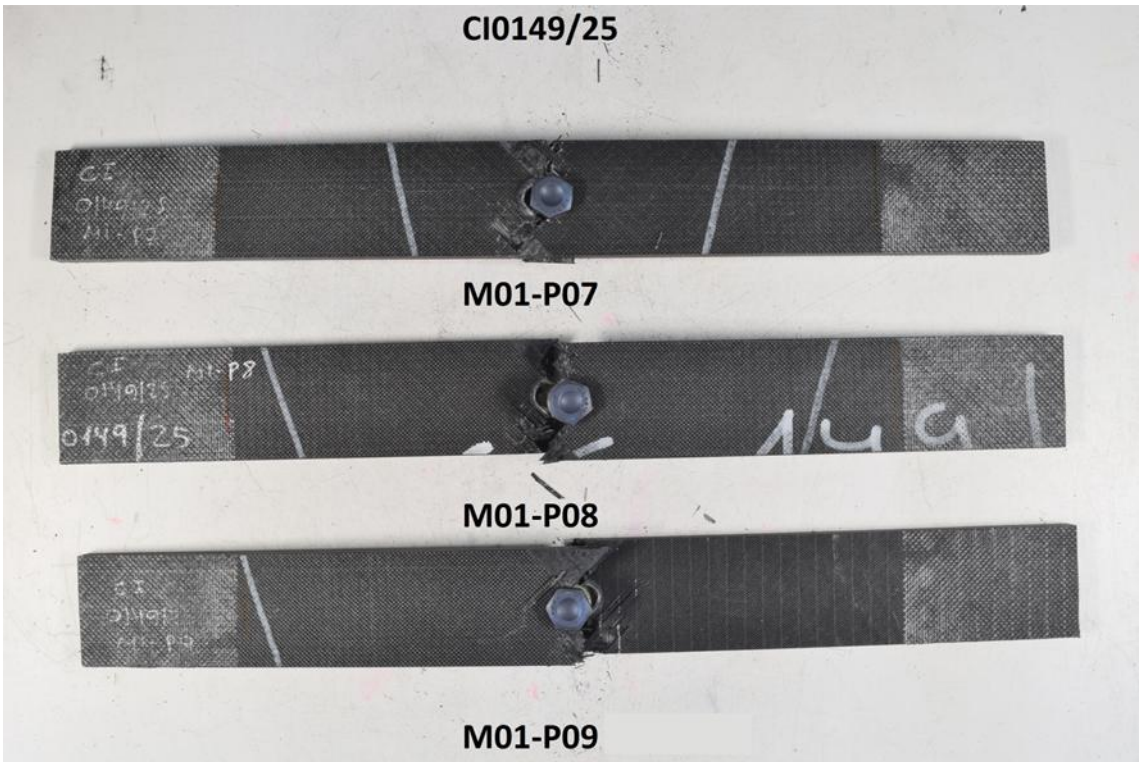

Figure 105. Failure mode for sensorised with microwires coupons – Batch 2. Tensile tests (FHT), WET/RT.

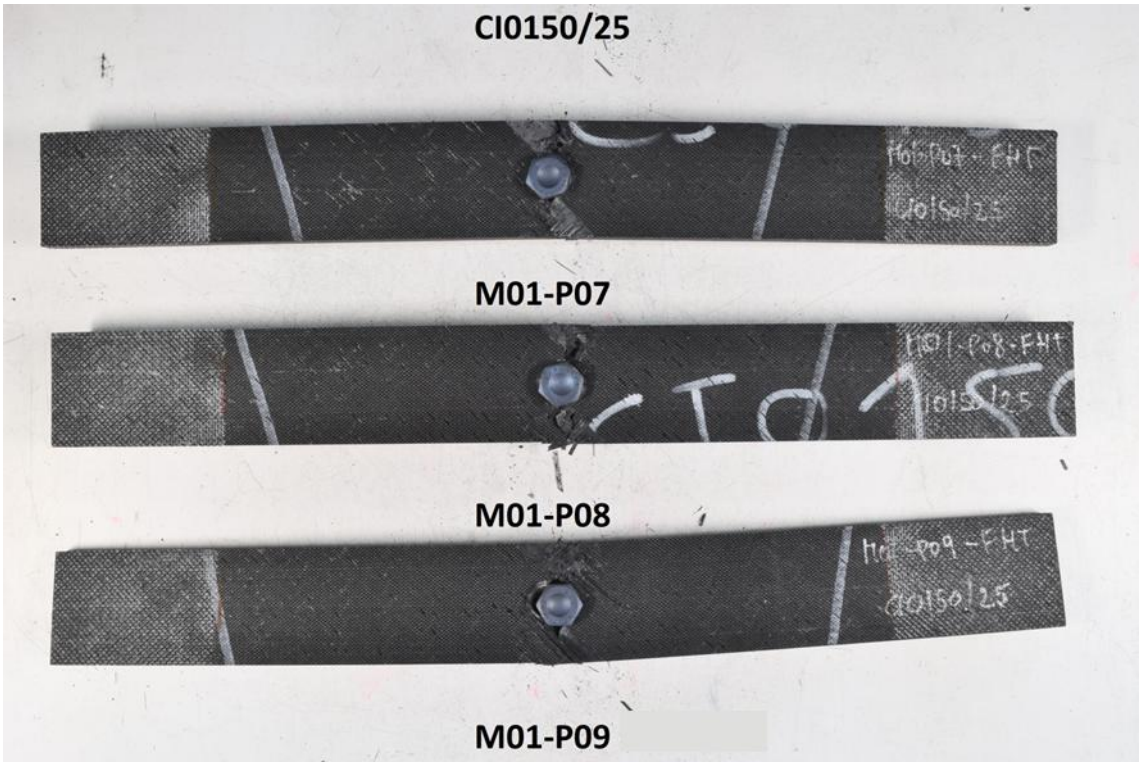

Figure 106. Failure mode for sensorised with microwires coupons – Batch 3. Tensile tests (FHT), WET/RT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

Figure 107. Failure mode for reference coupons – Batch 1. Compression tests (plain), RT.

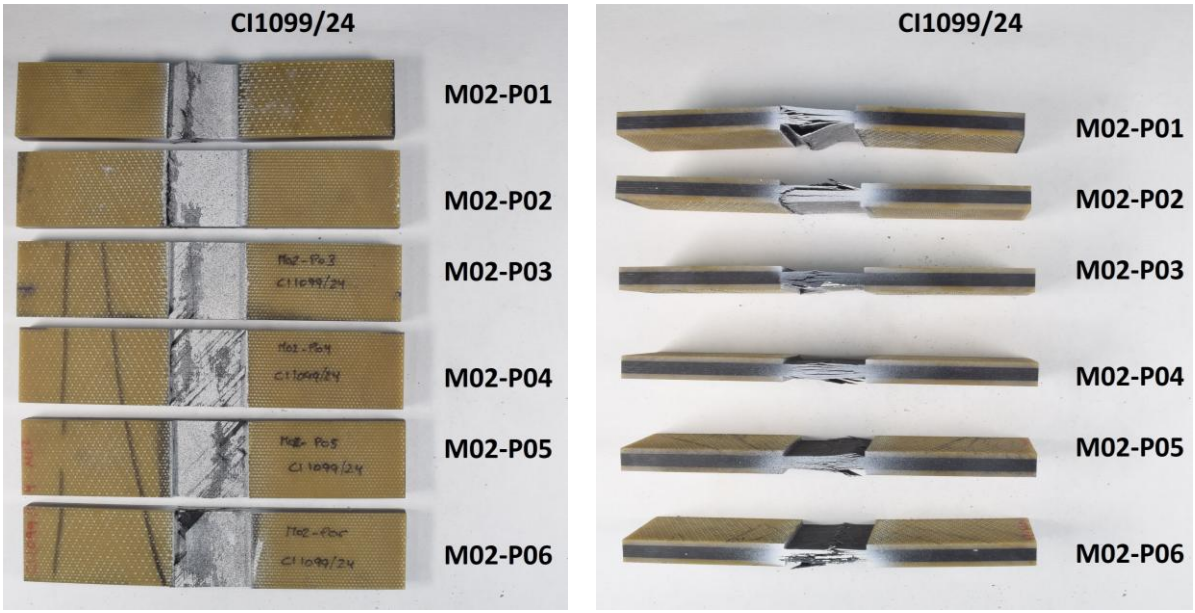

Figure 108. Failure mode for reference coupons – Batch 2. Compression tests (plain), RT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

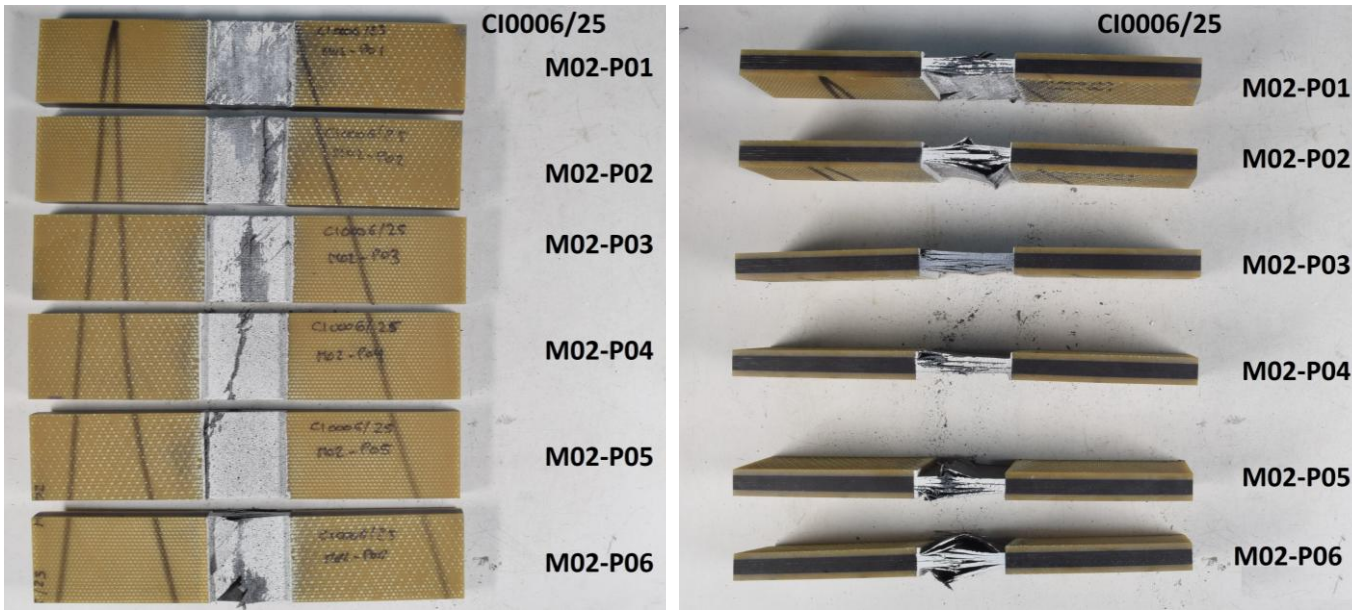

Figure 109. Failure mode for reference coupons – Batch 3. Compression tests (plain), RT.

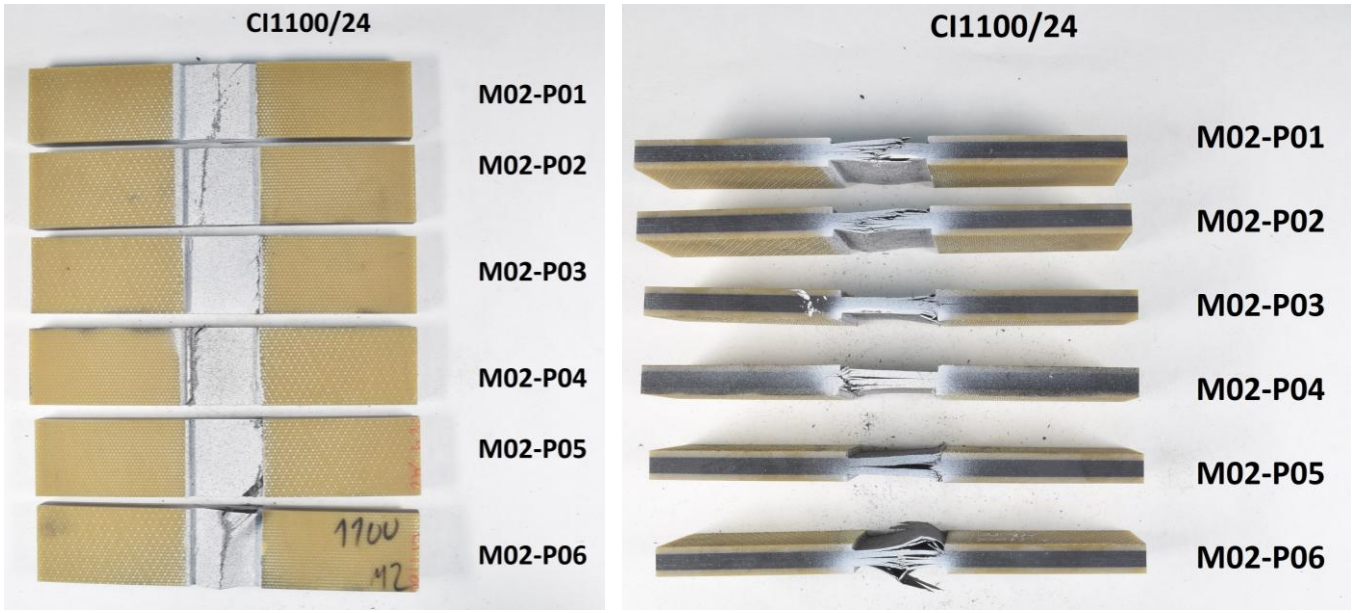

Figure 110. Failure mode for sensorised with microwires coupons – Batch 1. Compression tests (plain), RT.

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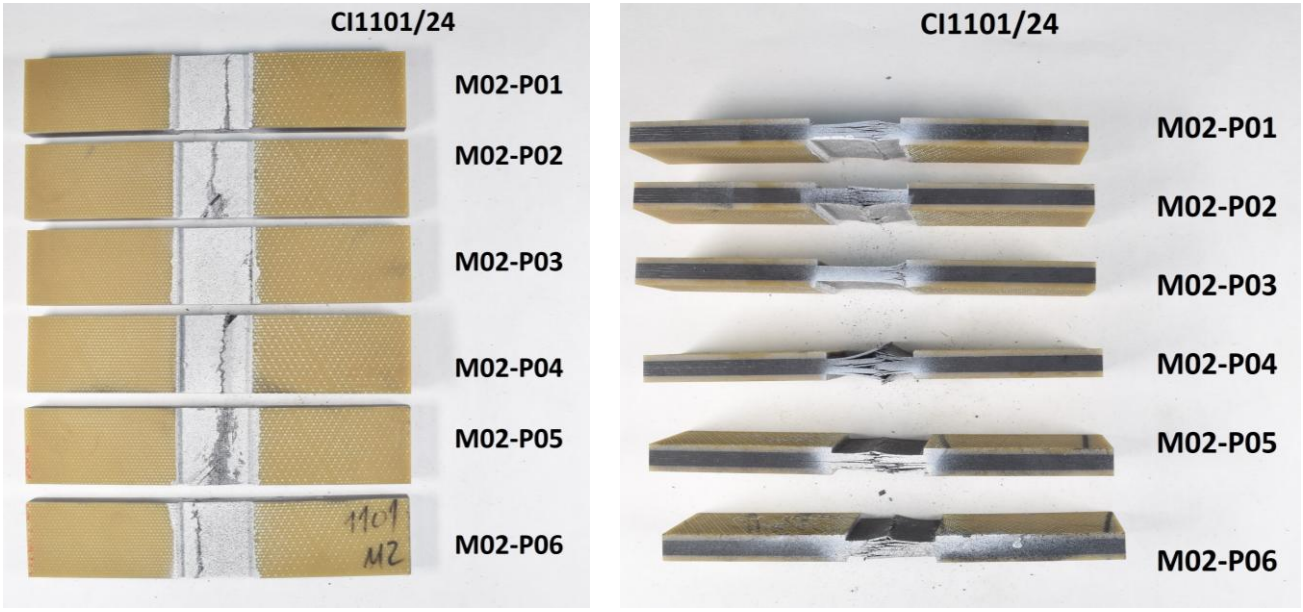

Figure 111. Failure mode for sensorised with microwires coupons – Batch 2. Compression tests (plain), RT.

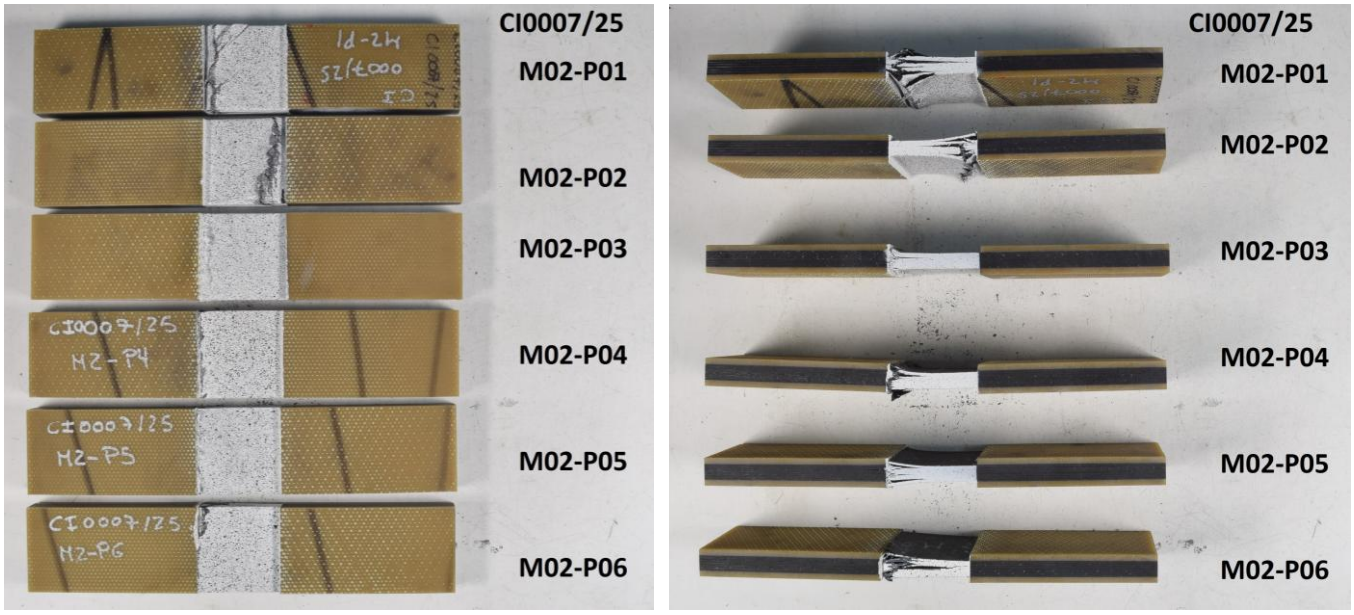

Figure 112. Failure mode for sensorised with microwires coupons – Batch 3. Compression tests (plain), RT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

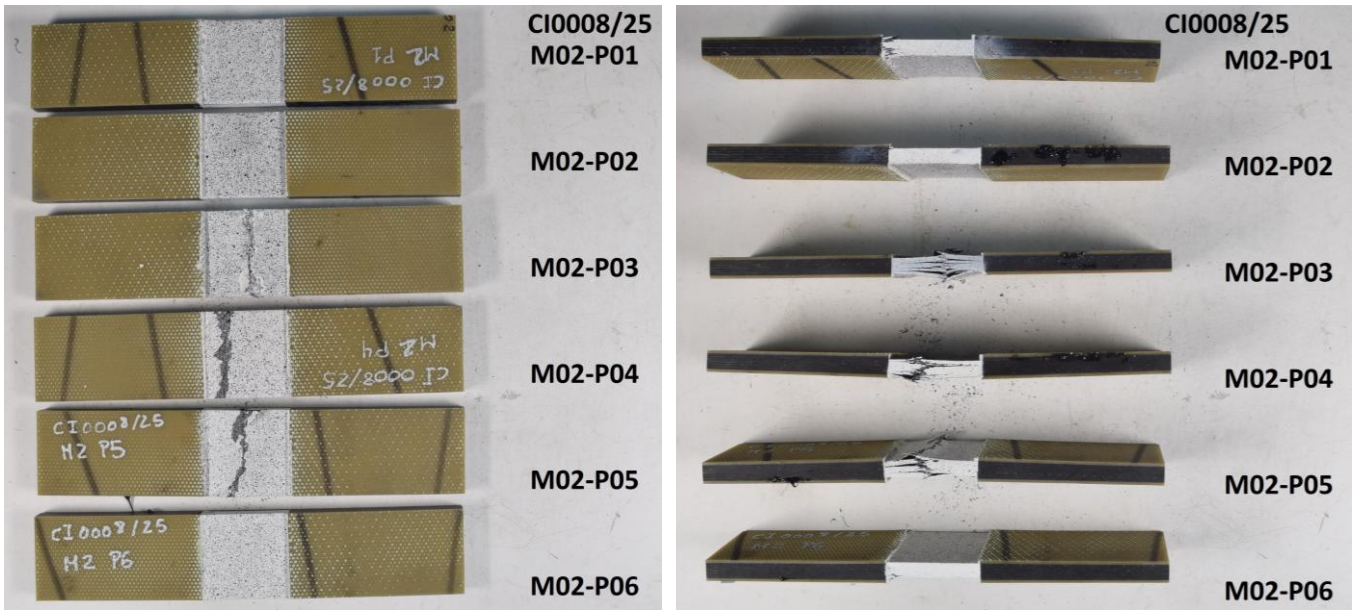

Figure 113. Failure mode for sensorised with microwires coupons – Batch 4. Compression tests (plain), RT.

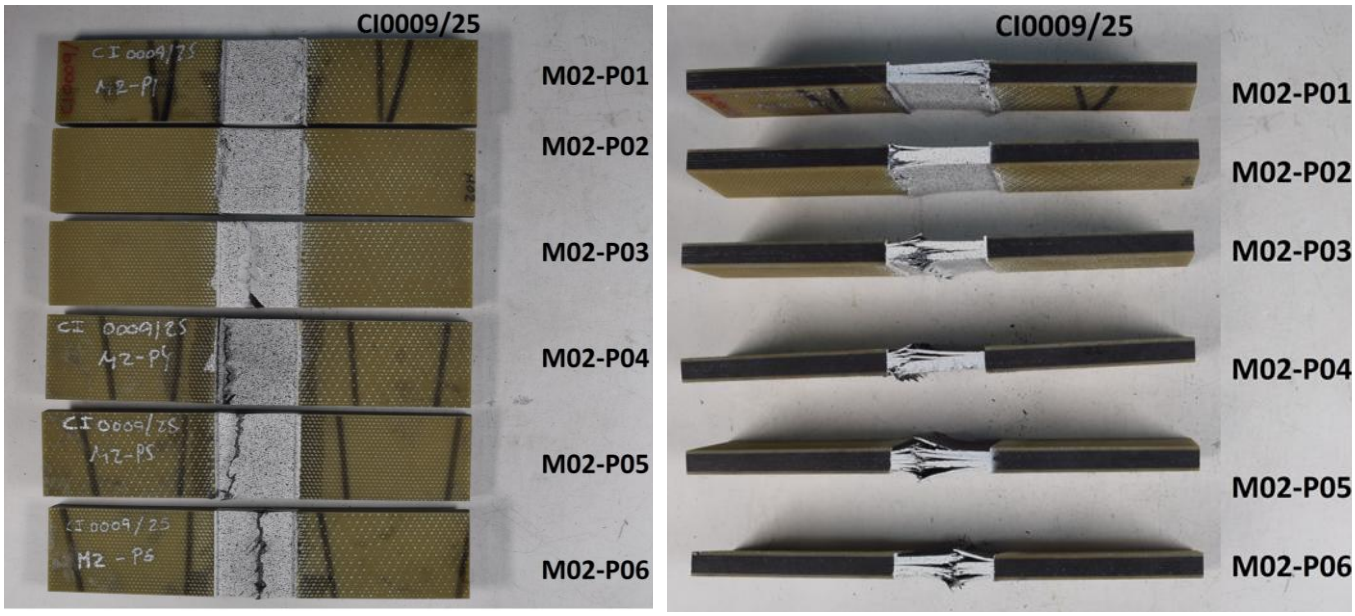

Figure 114. Failure mode for sensorised with microwires coupons – Batch 5. Compression tests (plain), RT.

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Figure 115. Failure mode for reference coupons – Batch 1. Compression tests (plain), LT.

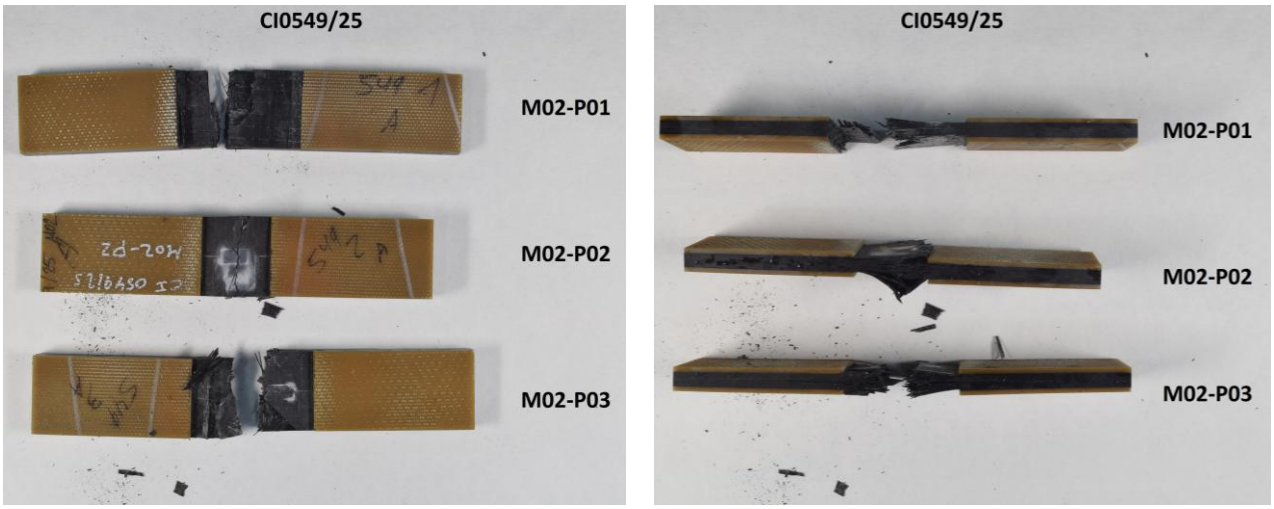

Figure 116. Failure mode for sensorised with microwires coupons – Batch 1. Compression tests (plain), LT.

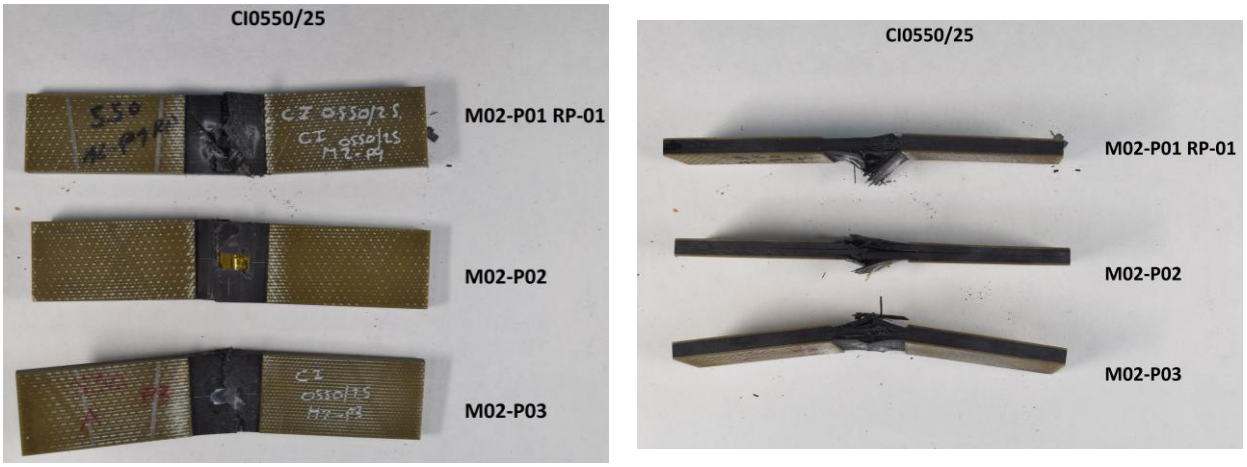

Figure 117. Failure mode for sensorised with microwires coupons – Batch 2. Compression tests (plain), LT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

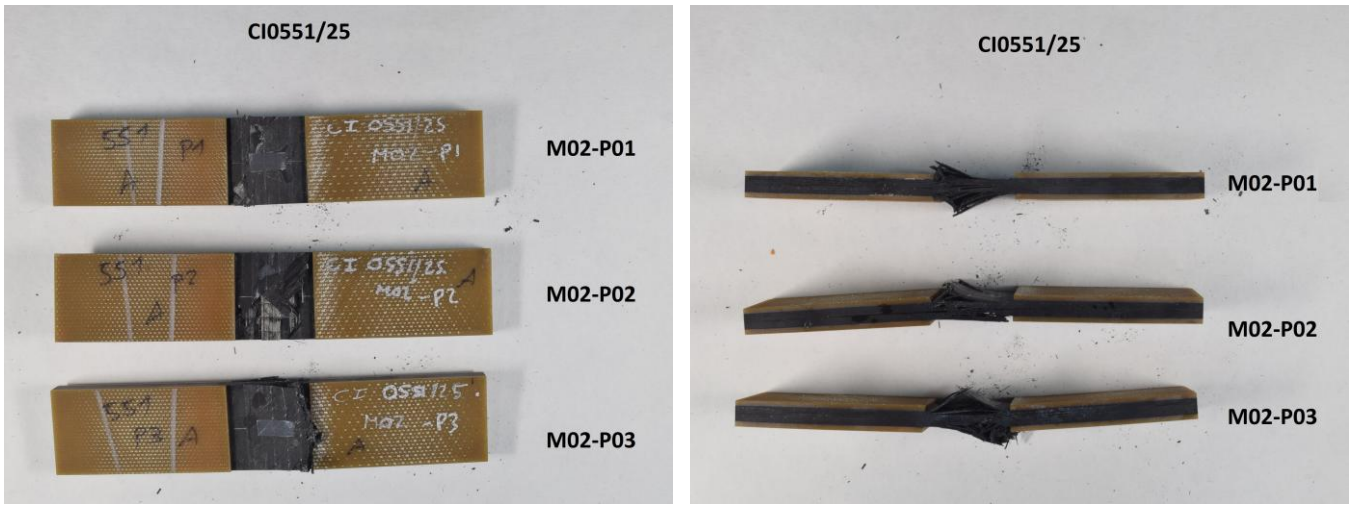

Figure 118. Failure mode for sensorised with microwires coupons – Batch 3. Compression tests (plain), LT.

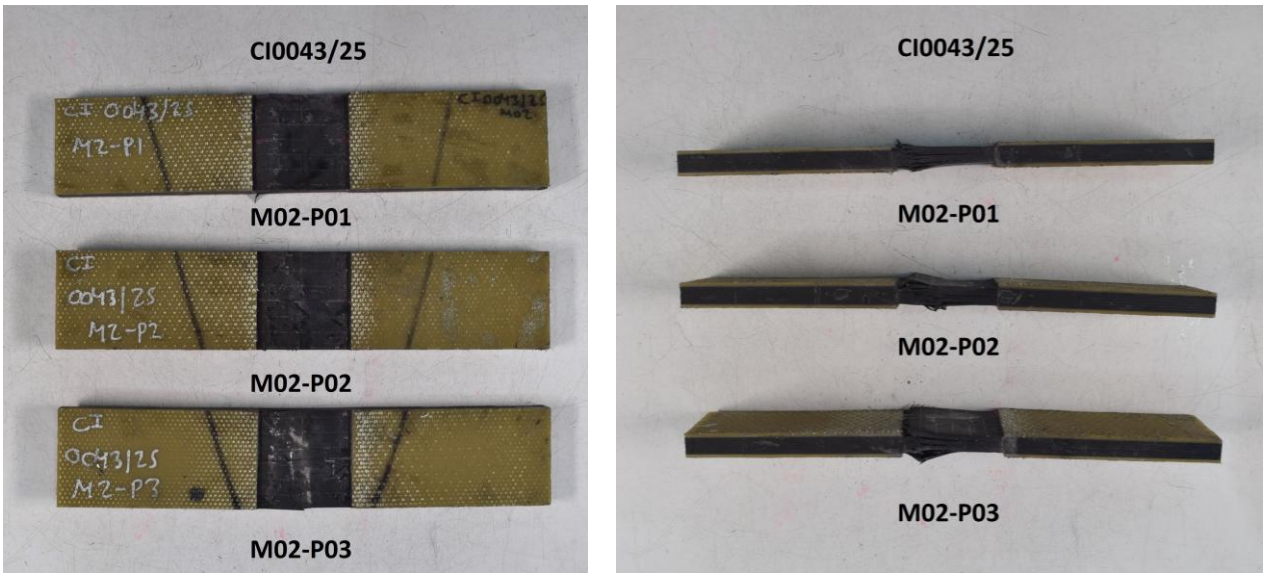

Figure 119. Failure mode for reference coupons – Batch 1. Compression tests (plain), WET/RT.

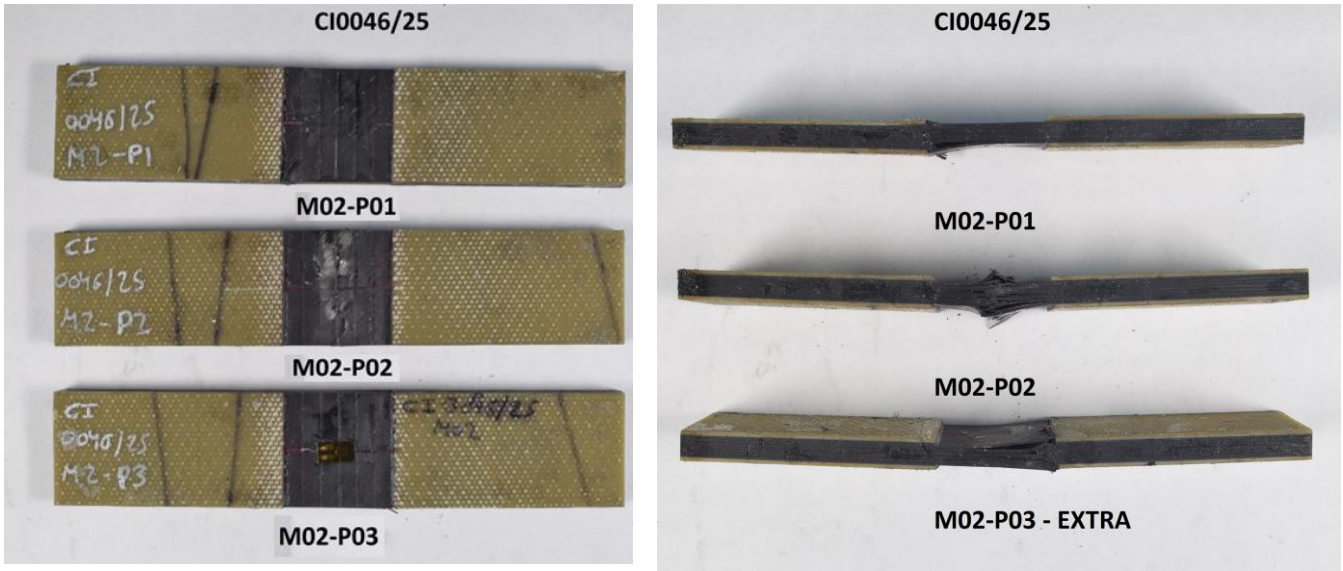

Figure 120. Failure mode for sensorised with microwires coupons – Batch 1. Compression tests (plain), WET/RT.

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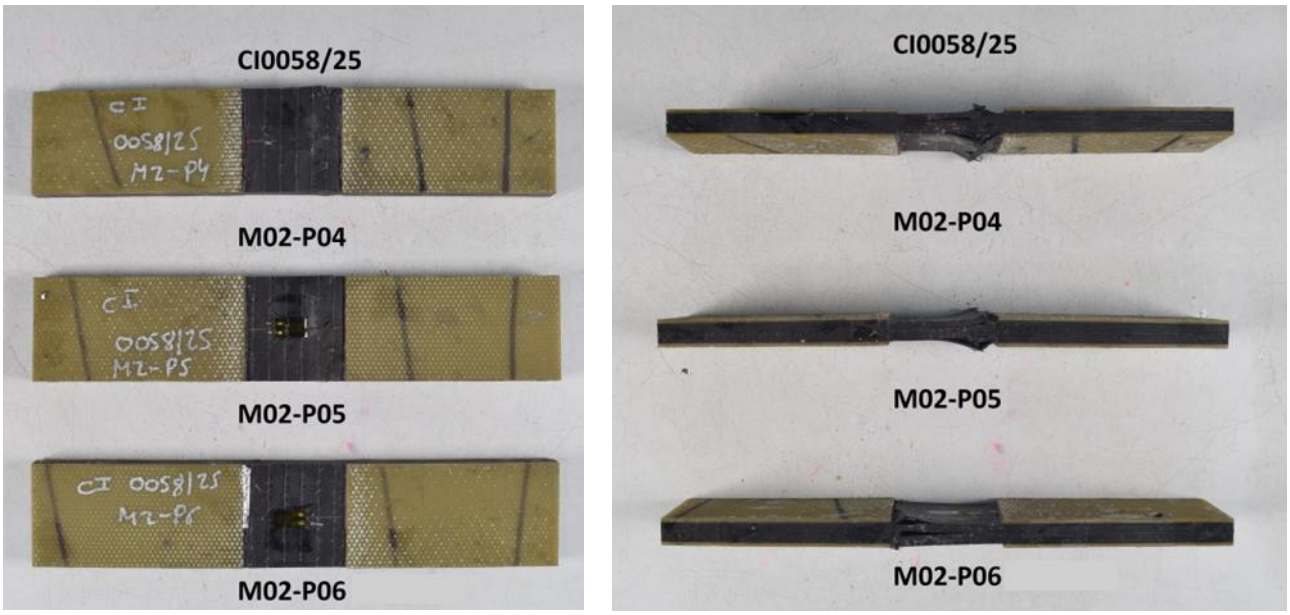

Figure 121. Failure mode for sensorised with microwires coupons – Batch 2. Compression tests (plain), WET/RT.

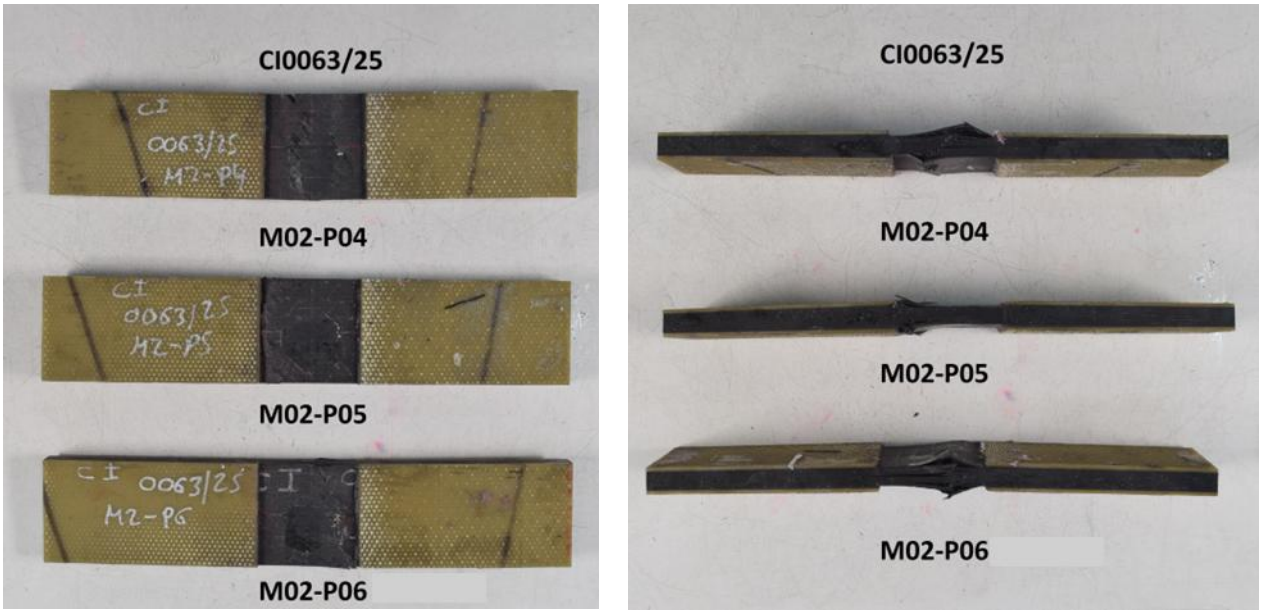

Figure 122. Failure mode for sensorised with microwires coupons – Batch 3. Compression tests (plain), WET/RT.

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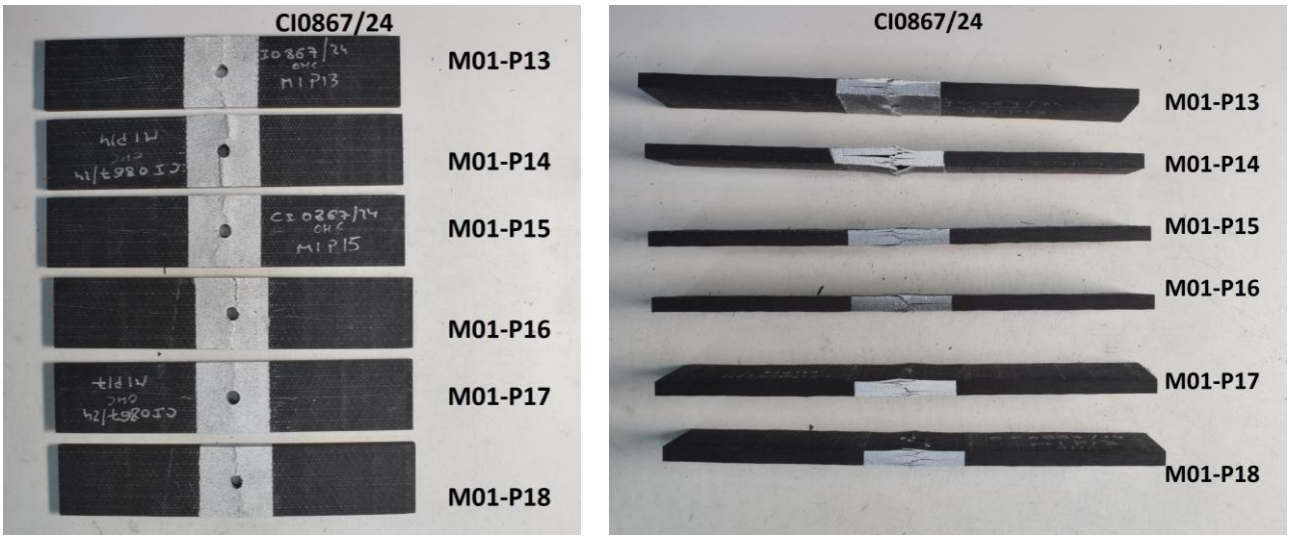

Figure 123. Failure mode for reference coupons – Batch 1. Compression tests (OHC), RT.

Figure 124. Failure mode for reference coupons – Batch 2. Compression tests (OHC), RT.

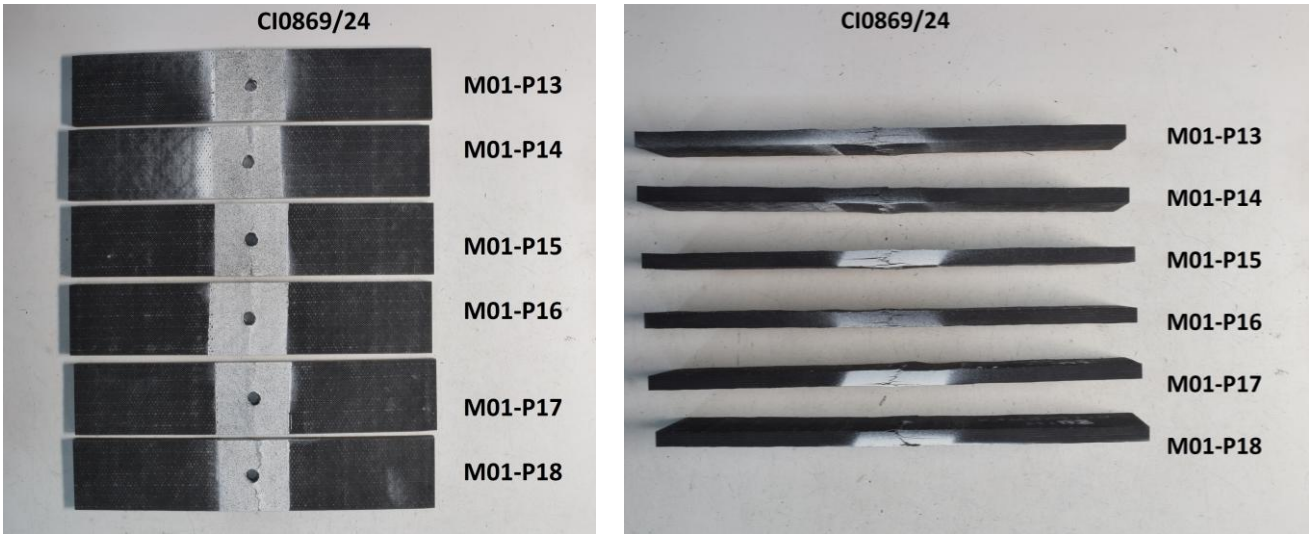

Figure 125. Failure mode for reference coupons – Batch 3. Compression tests (OHC), RT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

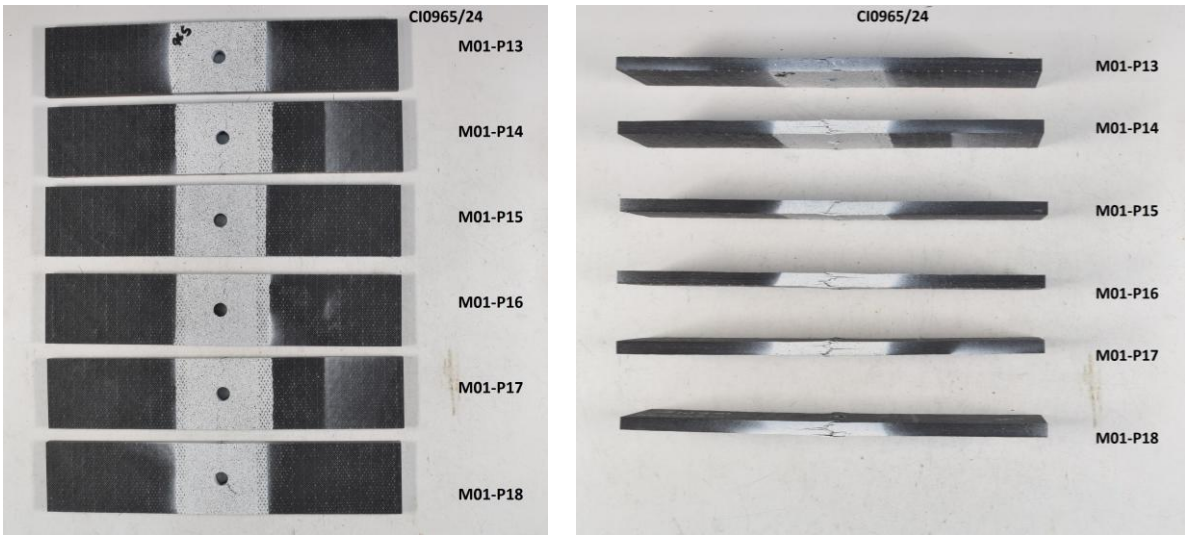

Figure 126. Failure mode for sensorised with microwires coupons – Batch 1. Compression tests (OHC), RT.

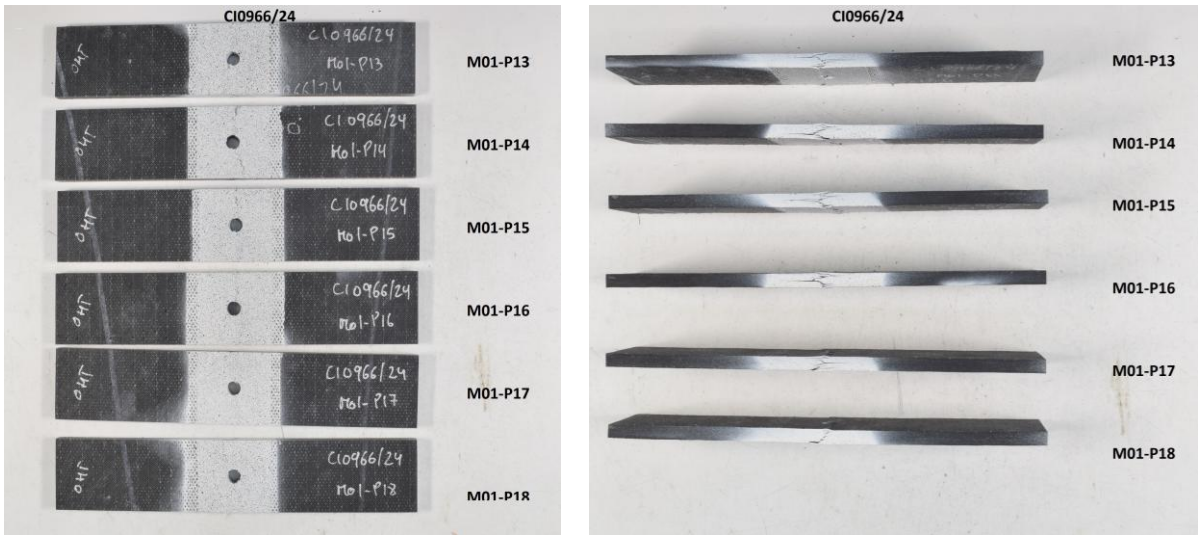

Figure 127. Failure mode for sensorised with microwires coupons – Batch 2. Compression tests (OHC), RT.

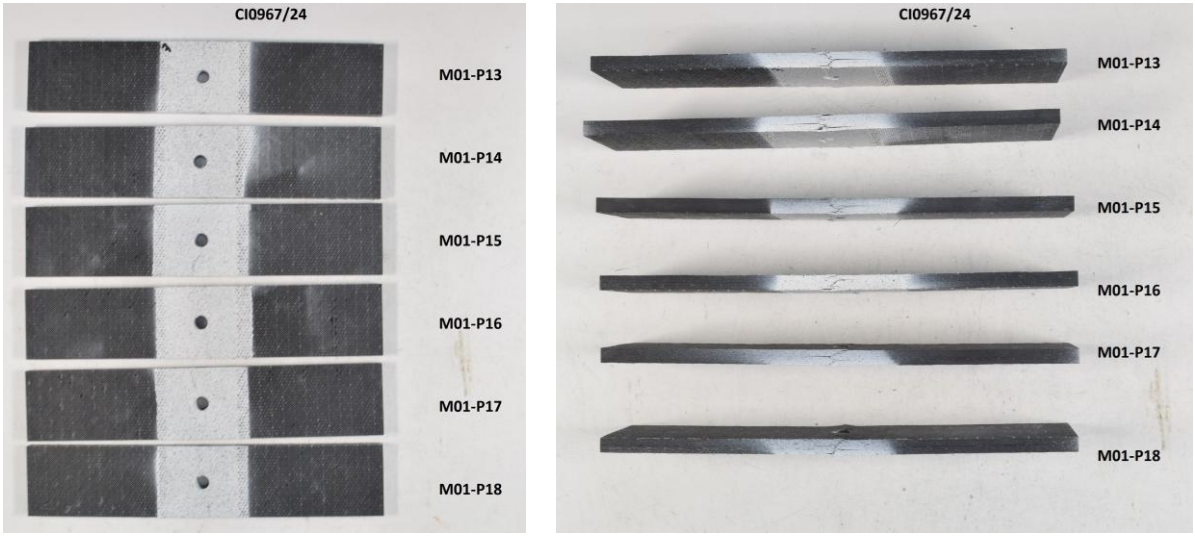

Figure 128. Failure mode for sensorised with microwires coupons – Batch 3. Compression tests (OHC), RT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

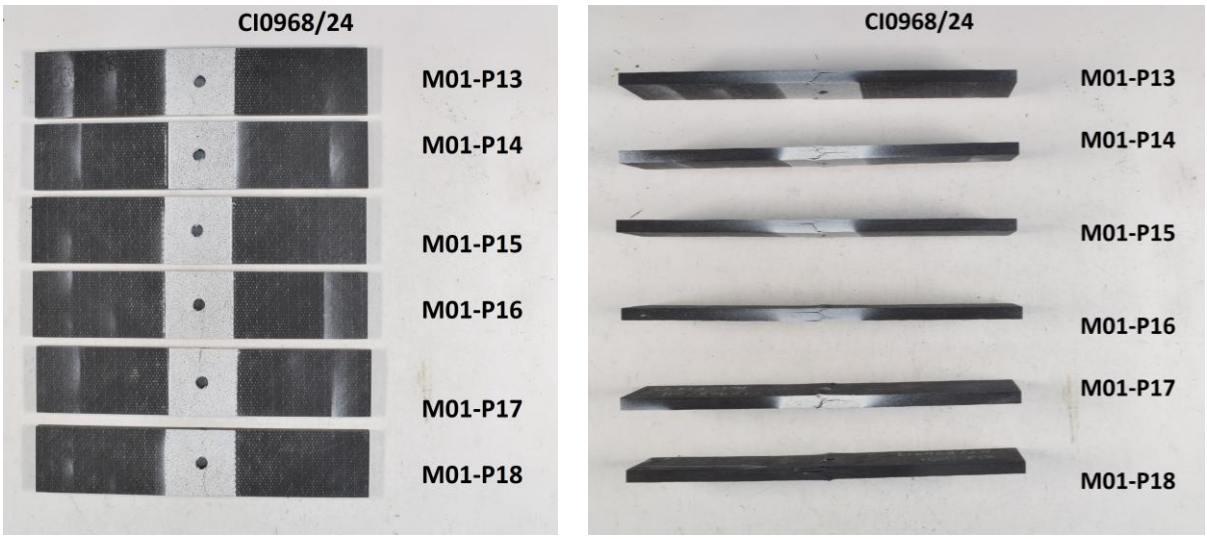

Figure 129. Failure mode for sensorised with microwires coupons – Batch 4. Compression tests (OHC), RT.

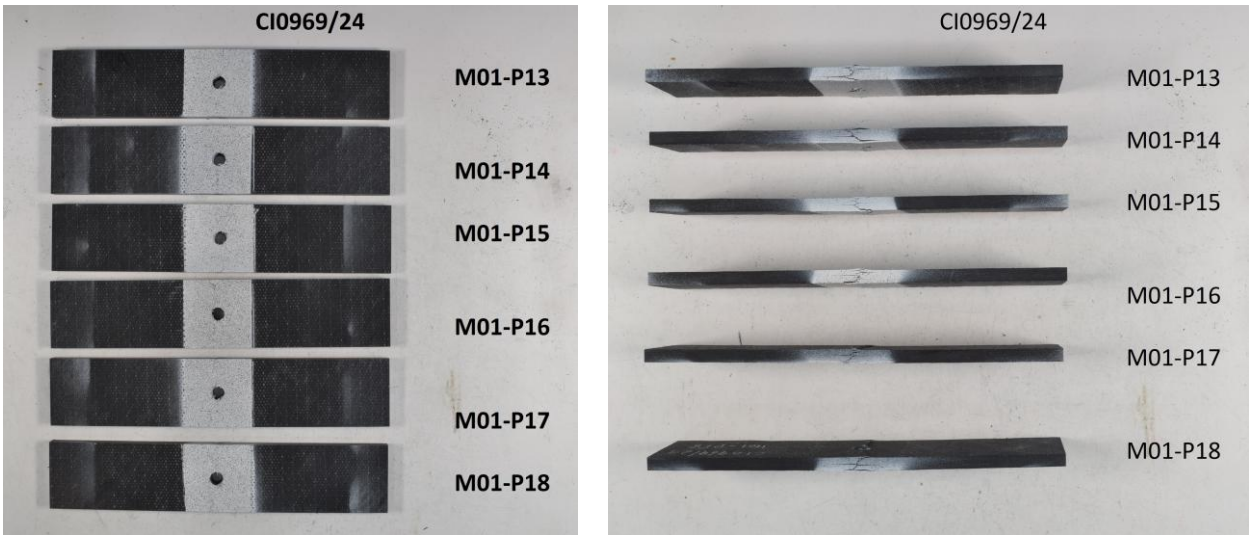

Figure 130. Failure mode for sensorised with microwires coupons – Batch 5. Compression tests (OHC), RT.

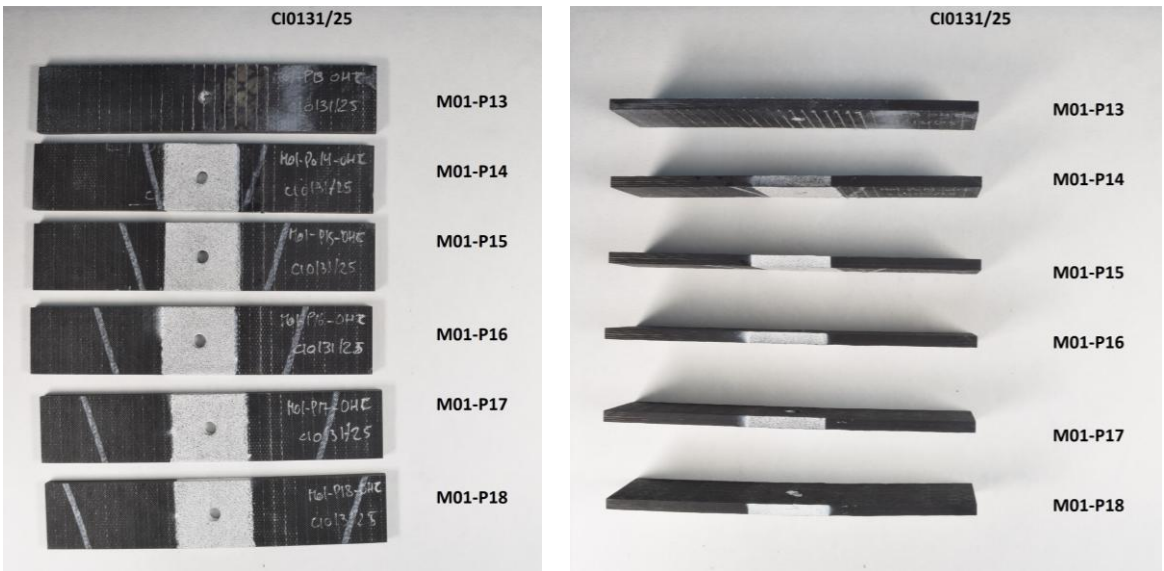

Figure 131. Failure mode for reference coupons – Batch 1. Compression tests (OHC), HT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

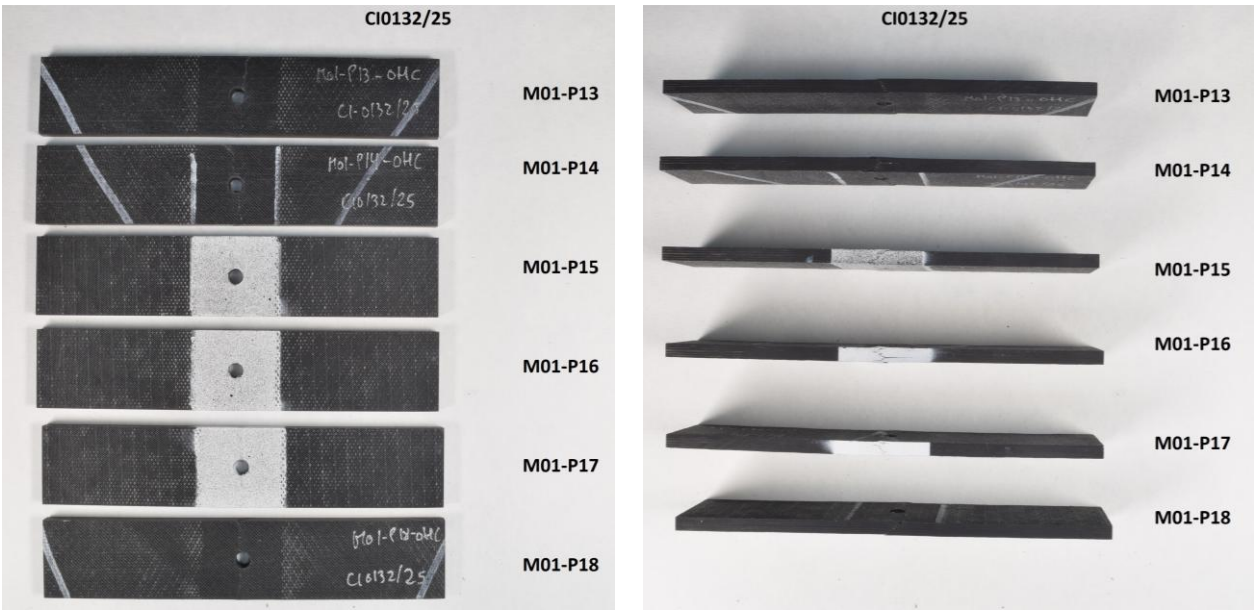

Figure 132. Failure mode for sensorised with microwires coupons – Batch 1. Compression tests (OHC), HT.

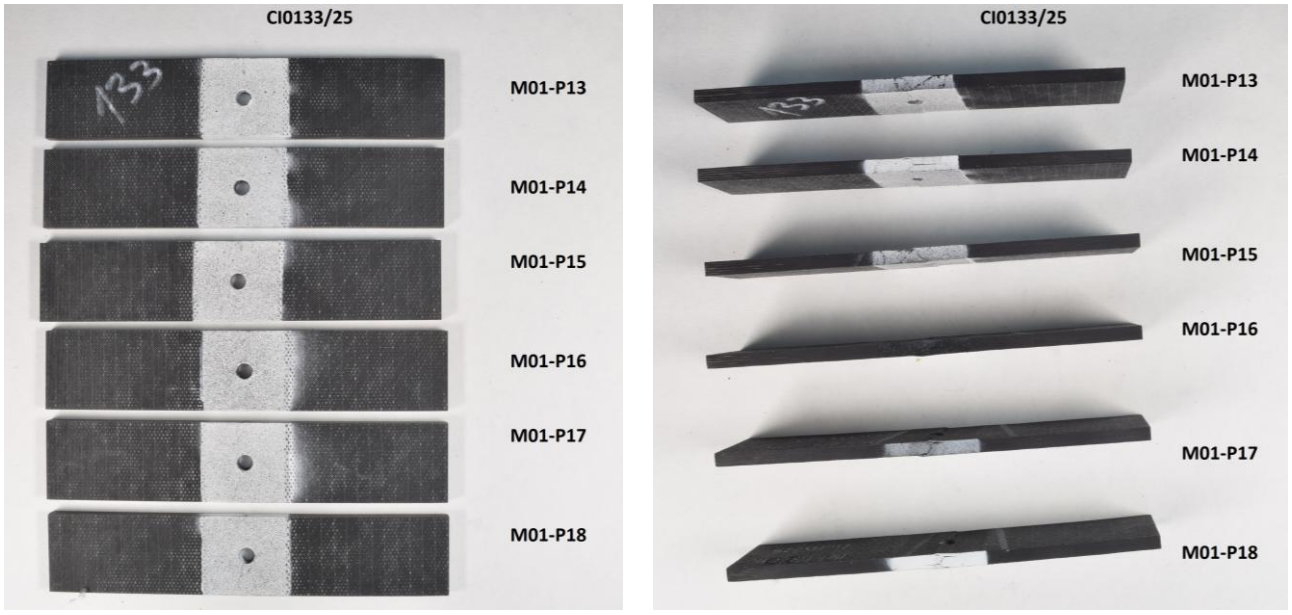

Figure 133. Failure mode for sensorised with microwires coupons – Batch 2. Compression tests (OHC), HT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

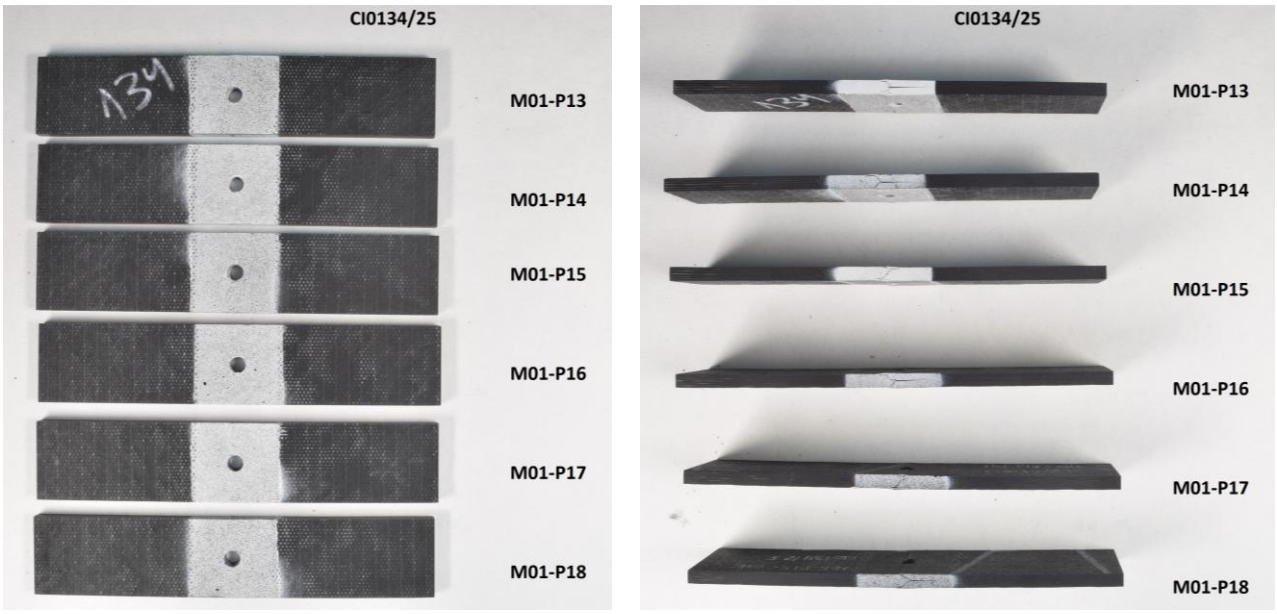

Figure 134. Failure mode for sensorised with microwires coupons – Batch 3. Compression tests (OHC), HT.

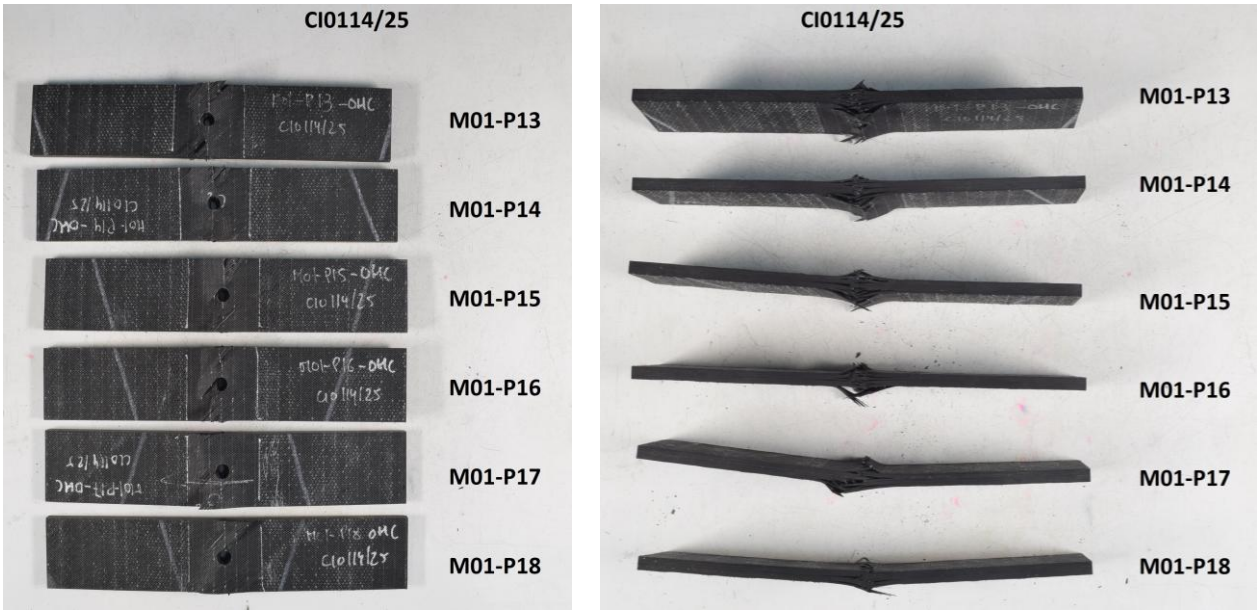

Figure 135. Failure mode for reference coupons – Batch 1. Compression tests (OHC), LT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

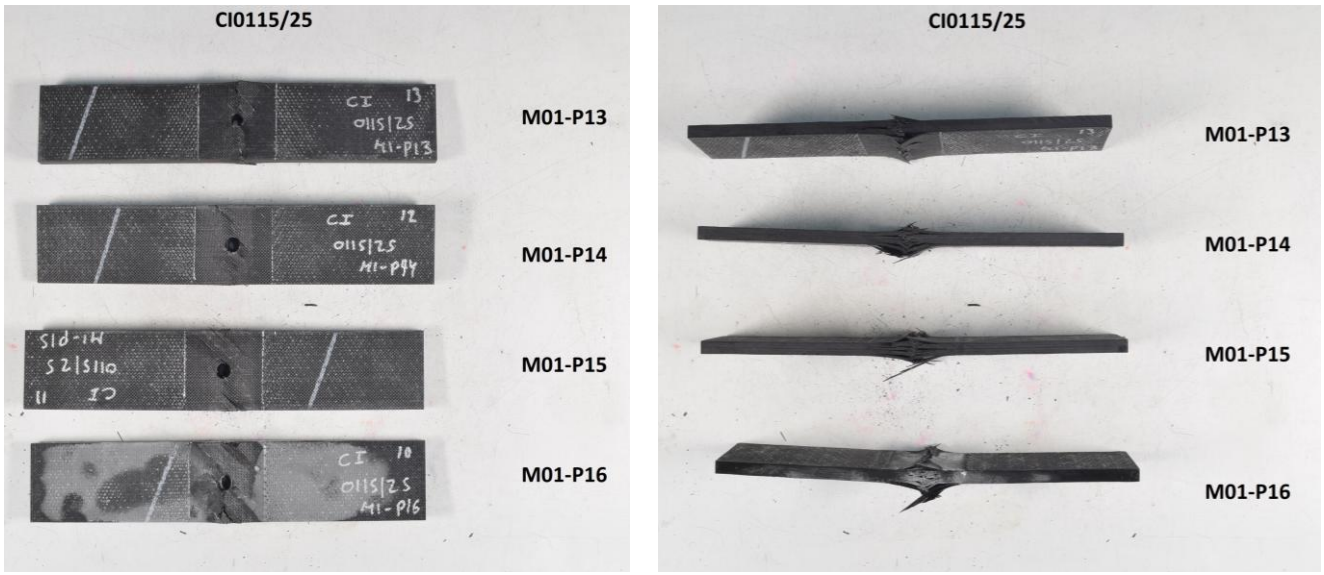

Figure 136. Failure mode for sensorised with microwires coupons – Batch 1. Compression tests (OHC), LT.

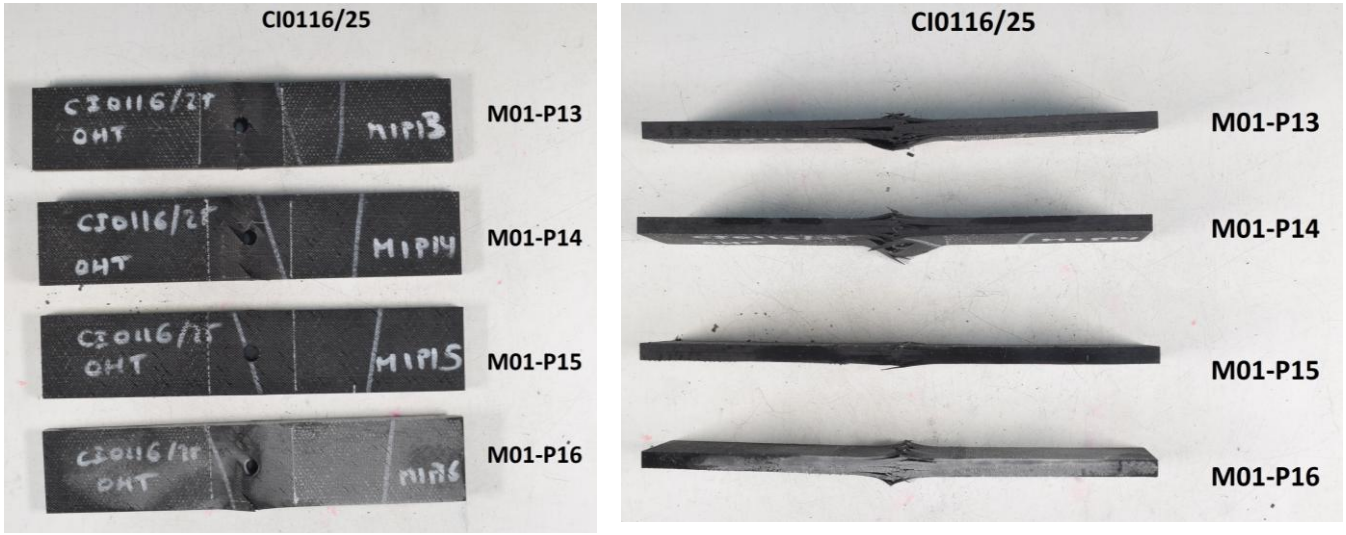

Figure 137. Failure mode for sensorised with microwires coupons – Batch 2. Compression tests (OHC), LT.

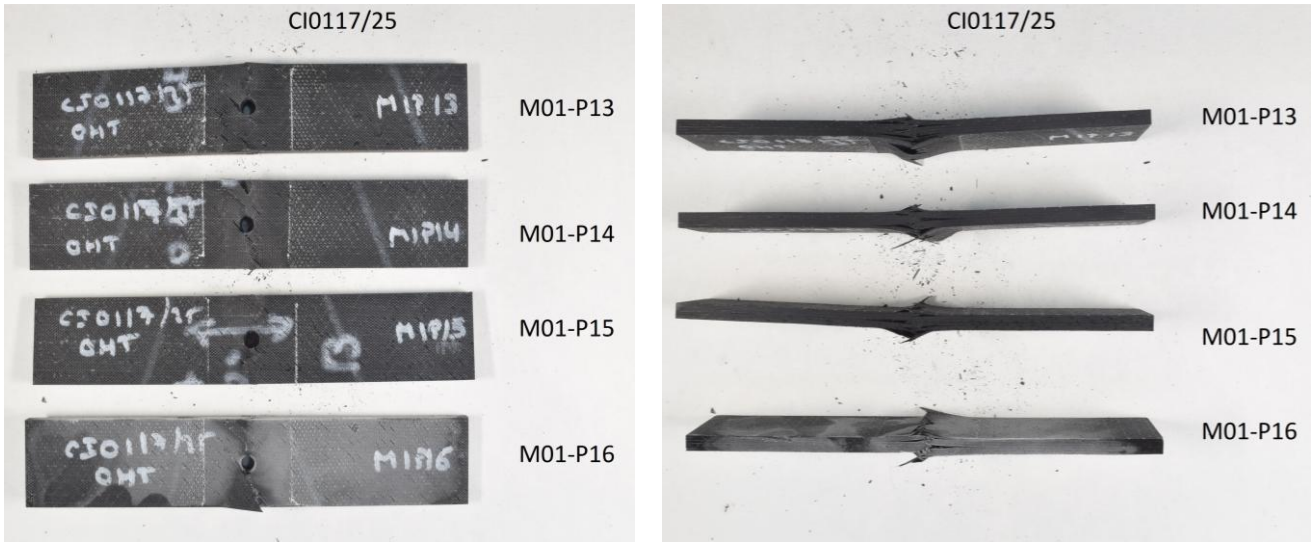

Figure 138. Failure mode for sensorised with microwires coupons – Batch 3. Compression tests (OHC), LT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

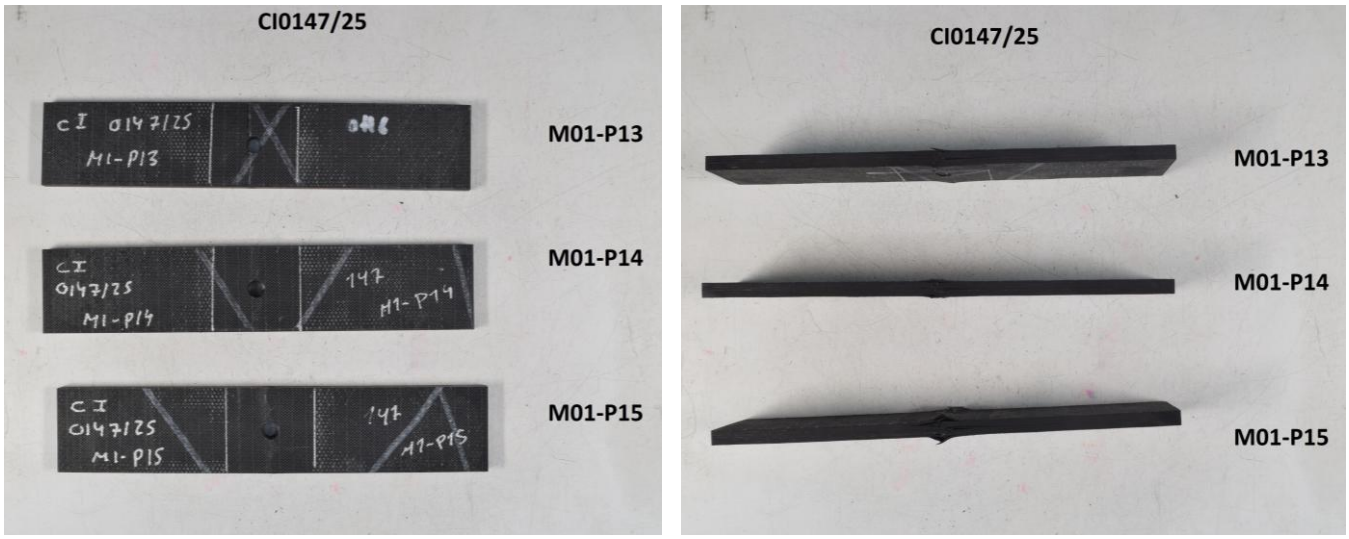

Figure 139. Failure mode for reference coupons – Batch 1. Compression tests (OHC), WET/RT.

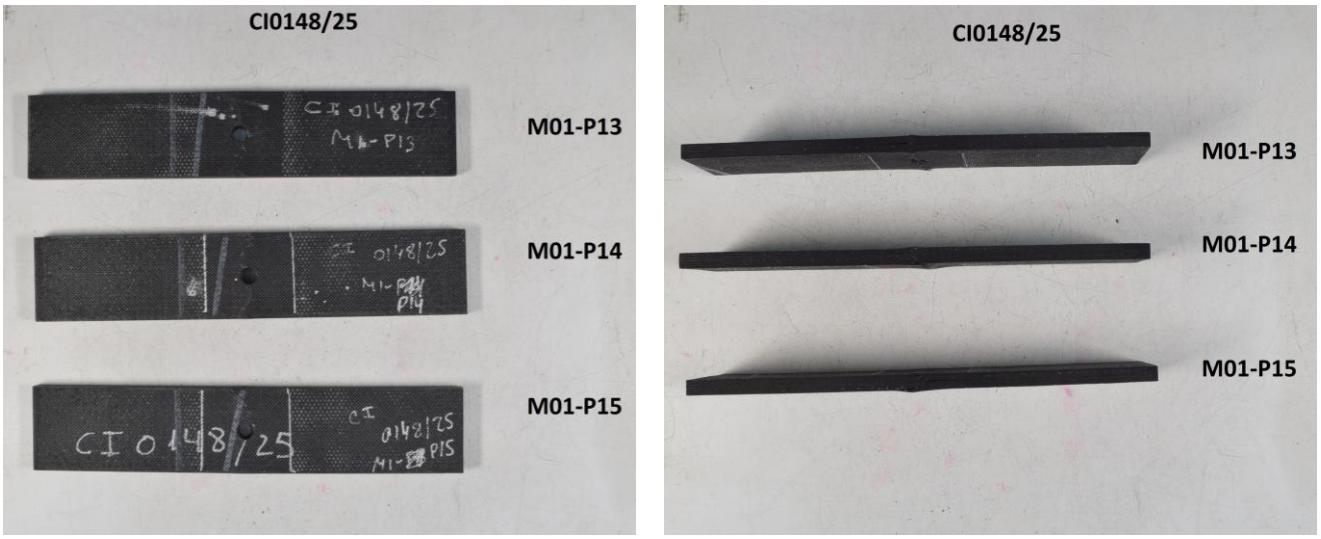

Figure 140. Failure mode for sensorised with microwires coupons – Batch 1. Compression tests (OHC), WET/RT.

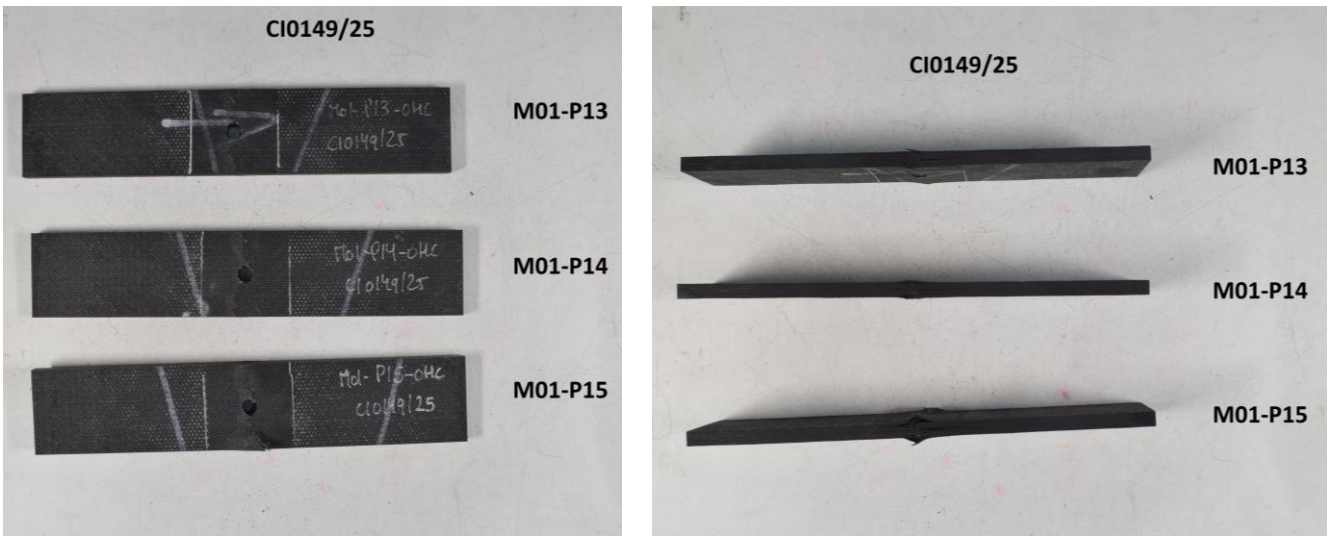

Figure 141. Failure mode for sensorised with microwires coupons – Batch 2. Compression tests (OHC), WET/RT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

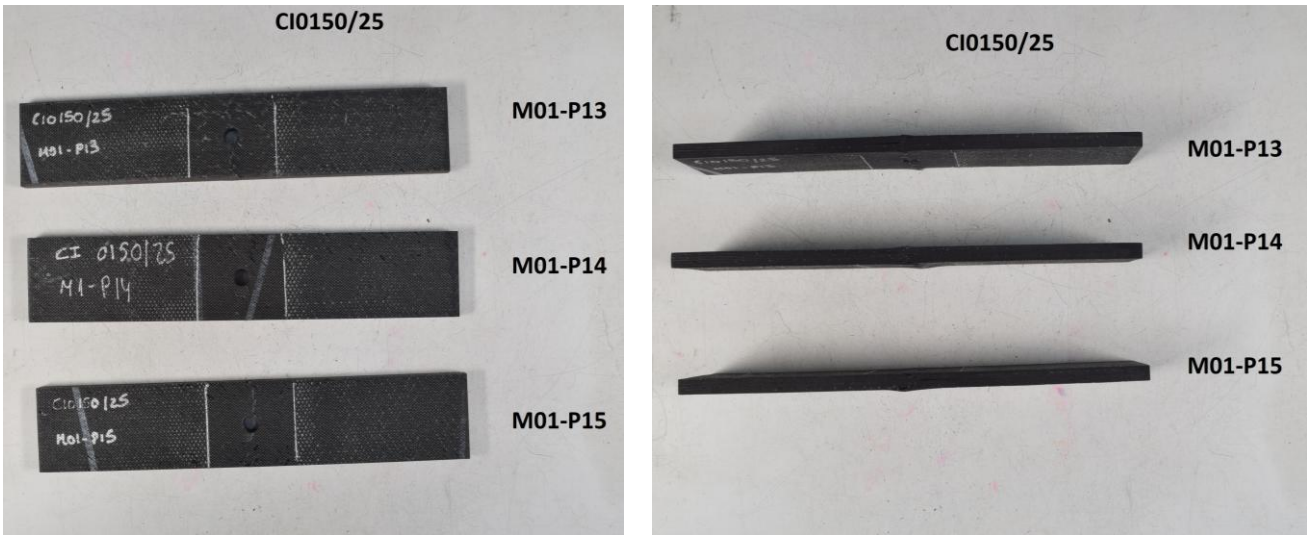

Figure 142. Failure mode for sensorised with microwires coupons – Batch 3. Compression tests (OHC), WET/RT.

Figure 143. Failure mode for reference coupons – Batch 1. Compression tests (FHC), RT.

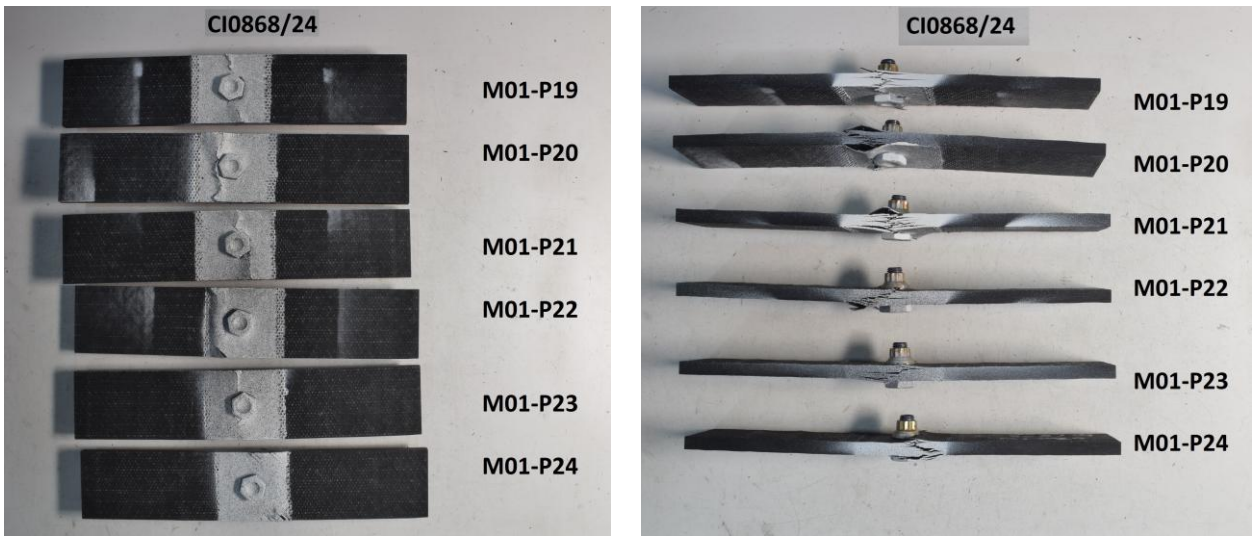

Figure 144. Failure mode for reference coupons – Batch 2. Compression tests (FHC), RT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

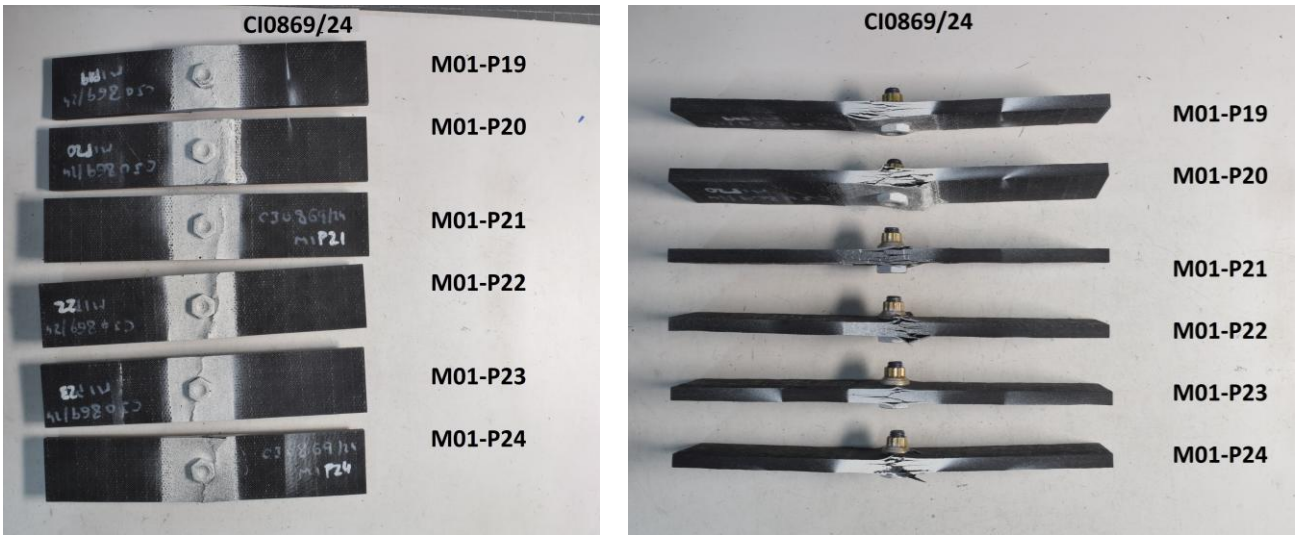

Figure 145. Failure mode for reference coupons – Batch 3. Compression tests (FHC), RT.

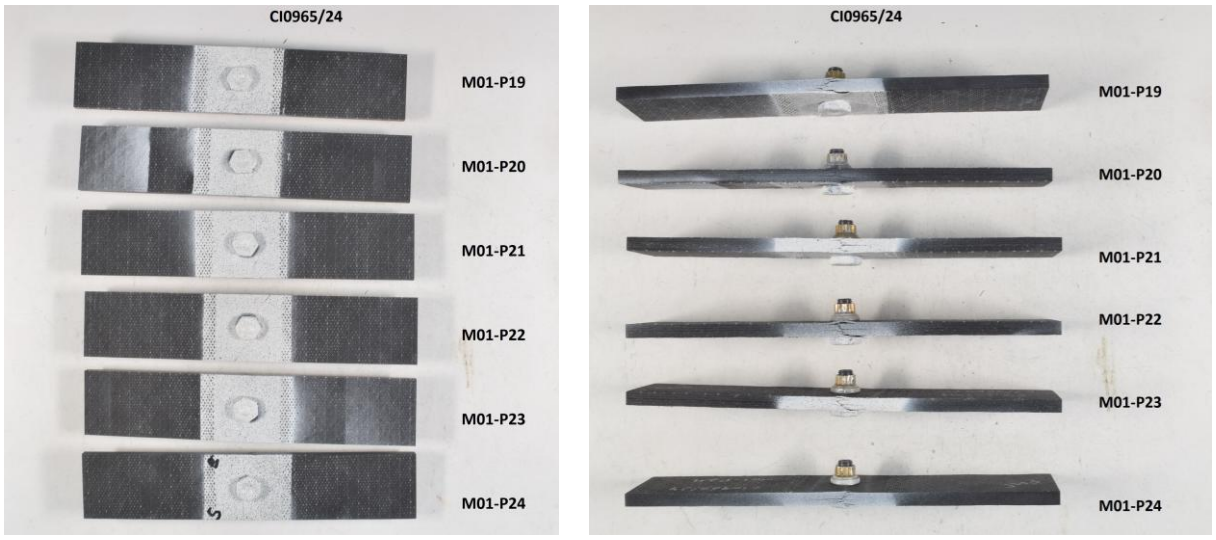

Figure 146. Failure mode for sensorised with microwires coupons – Batch 1. Compression tests (FHC), RT.

Figure 147. Failure mode for sensorised with microwires coupons – Batch 2. Compression tests (FHC), RT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

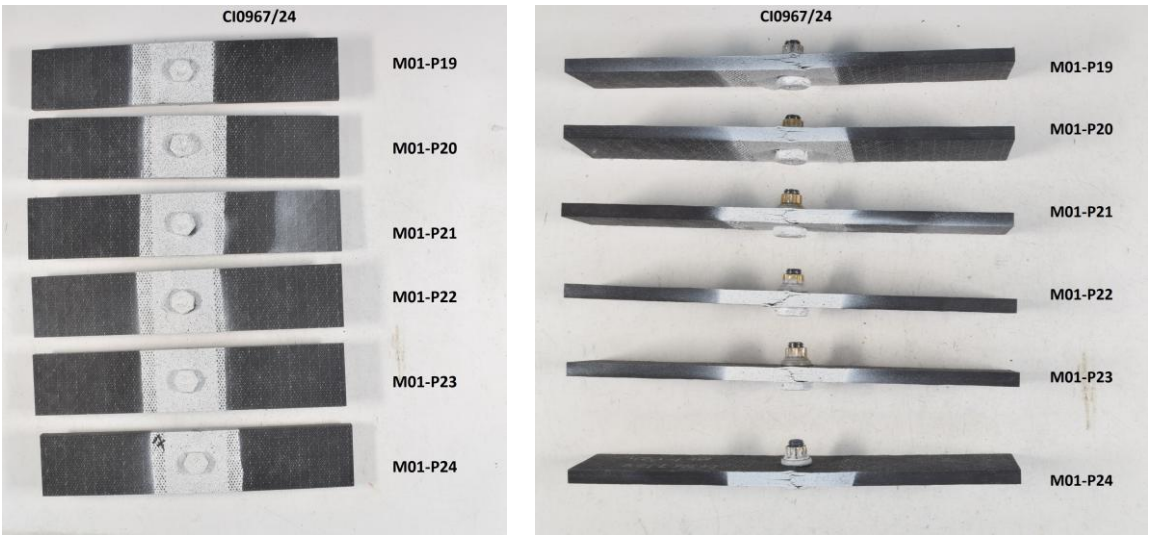

Figure 148. Failure mode for sensorised with microwires coupons – Batch 3. Compression tests (FHC), RT.

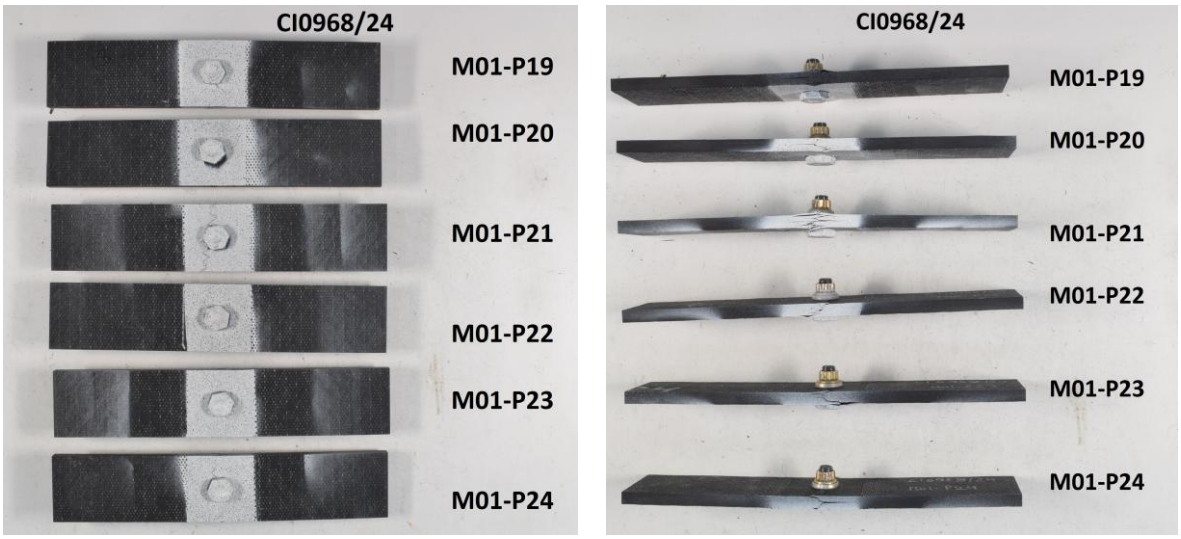

Figure 149. Failure mode for sensorised with microwires coupons – Batch 4. Compression tests (FHC), RT.

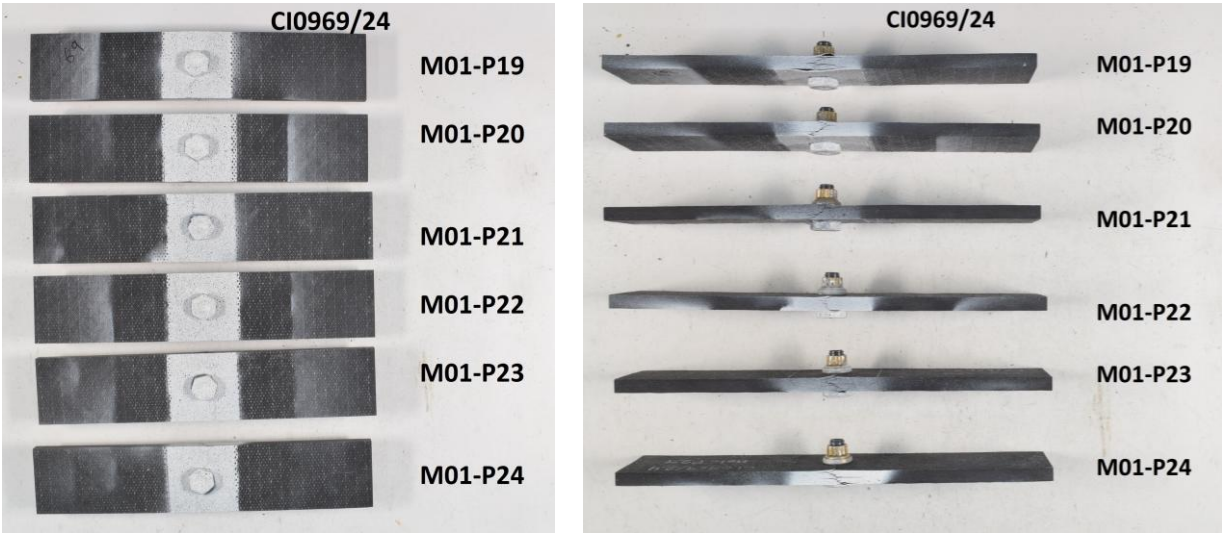

Figure 150. Failure mode for sensorised with microwires coupons – Batch 5. Compression tests (FHC), RT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

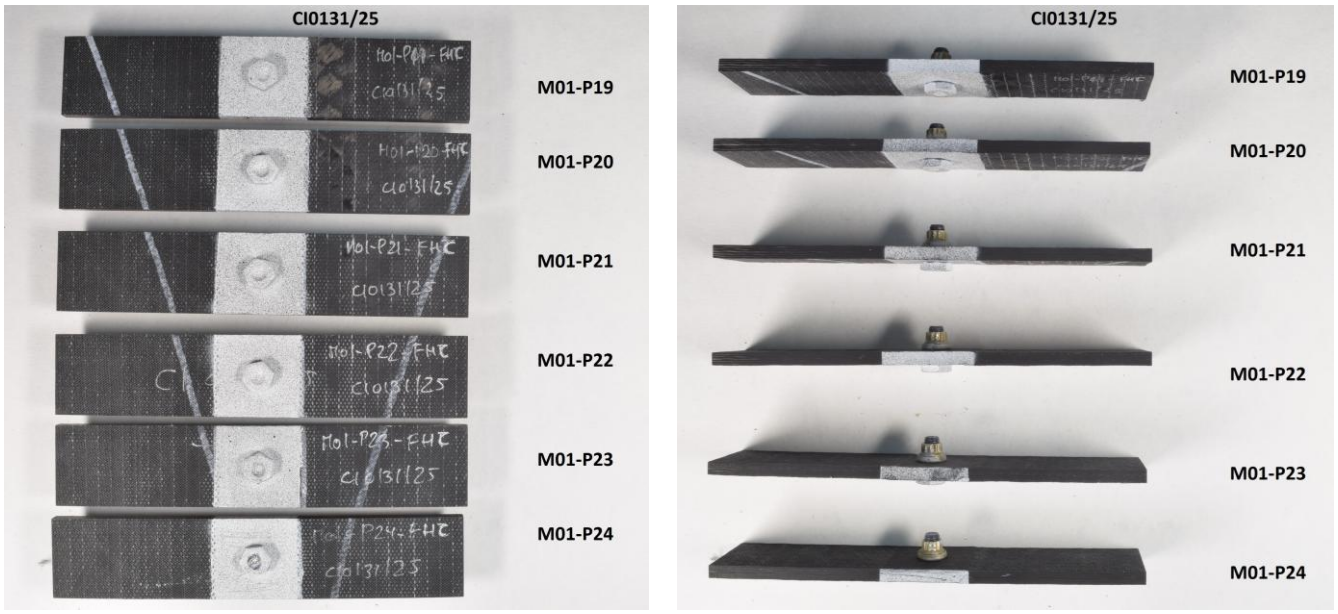

Figure 151. Failure mode for reference coupons – Batch 1. Compression tests (FHC), HT.

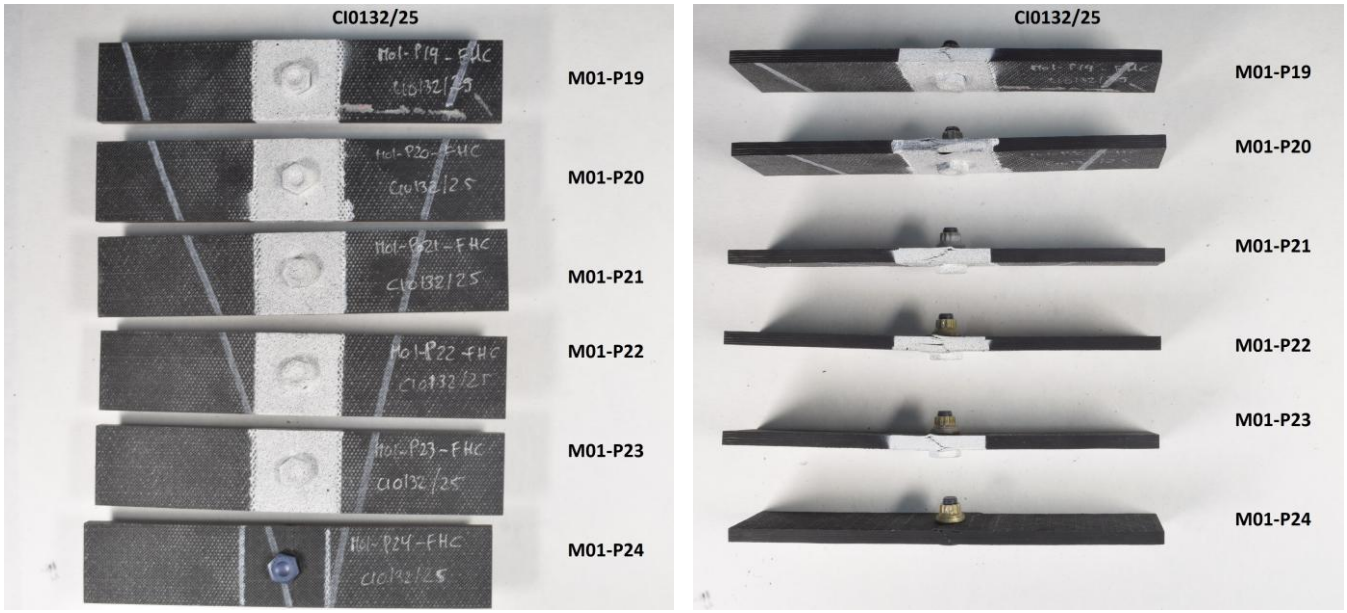

Figure 152. Failure mode for sensorised with microwires coupons – Batch 1. Compression tests (FHC), HT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

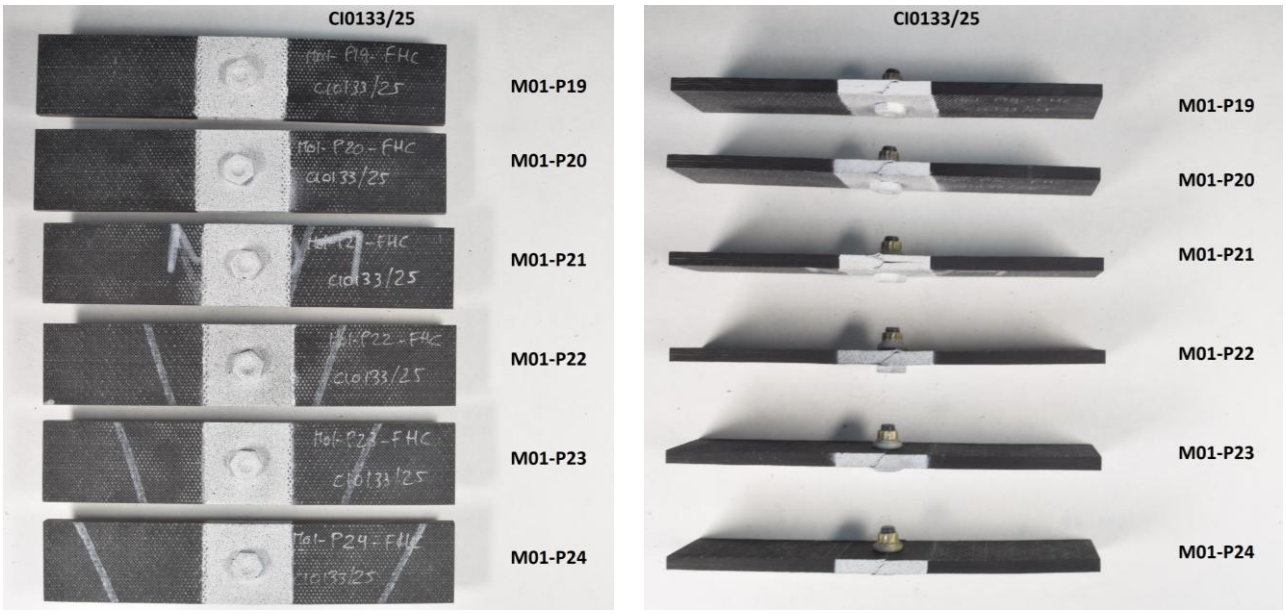

Figure 153. Failure mode for sensorised with microwires coupons – Batch 2. Compression tests (FHC), HT.

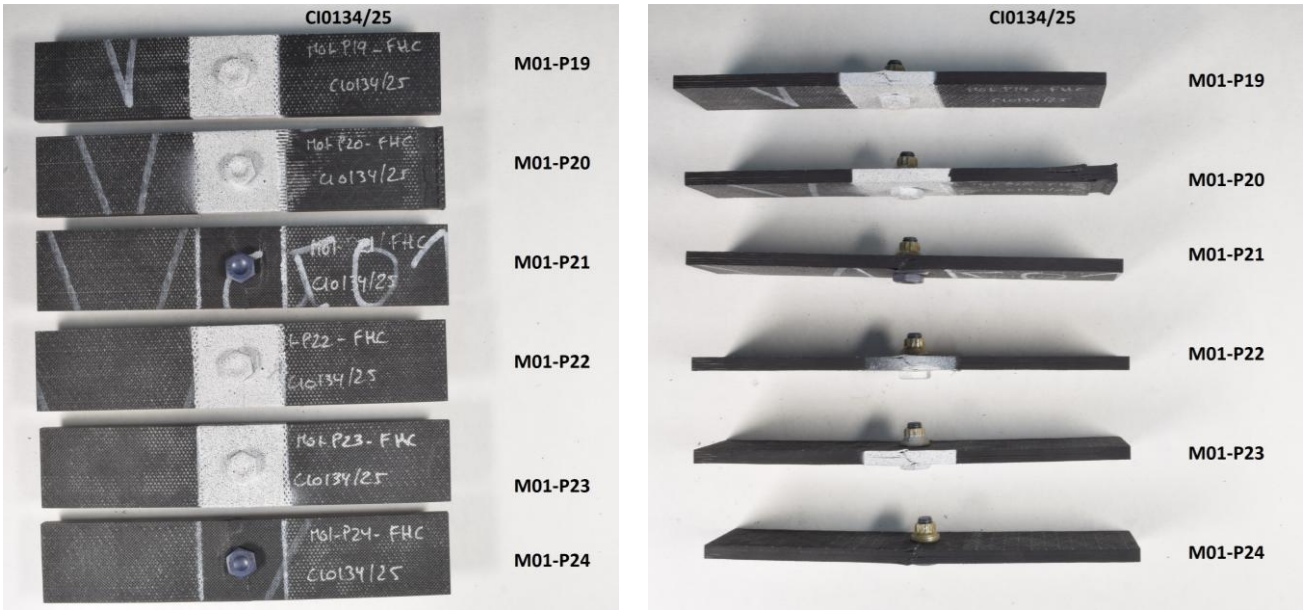

Figure 154. Failure mode for sensorised with microwires coupons – Batch 3. Compression tests (FHC), HT.

This project has received funding from the European Union´s Horizon Europe Research and Innovation Programme under grant agreement Nº. 101056884 and it is an initiative of the factories-of-the Future (FoF) Public Private Partnership.

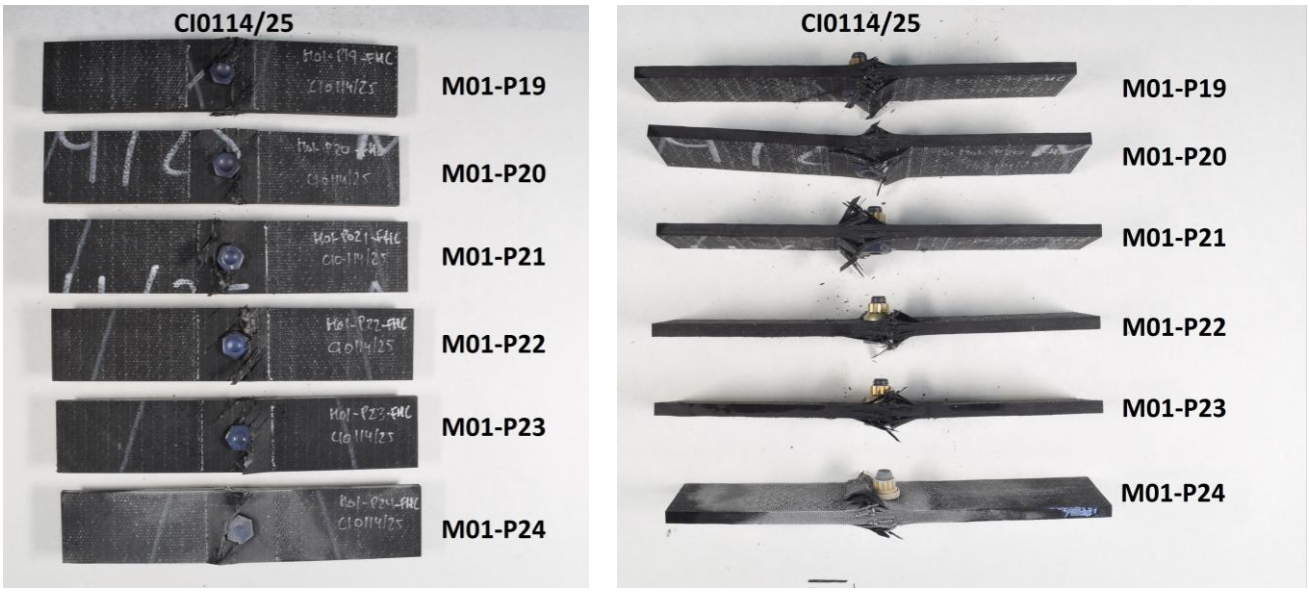

Figure 155. Failure mode for reference coupons – Batch 1. Compression tests (FHC), LT.

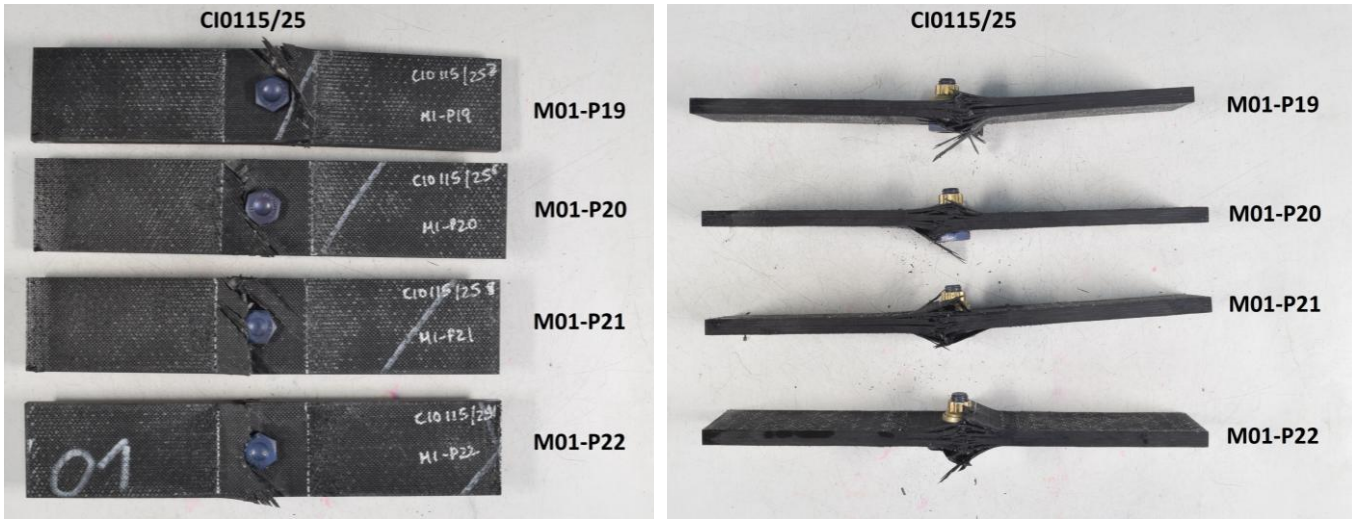

Figure 156. Failure mode for sensorised with microwires coupons – Batch 1. Compression tests (FHC), LT.

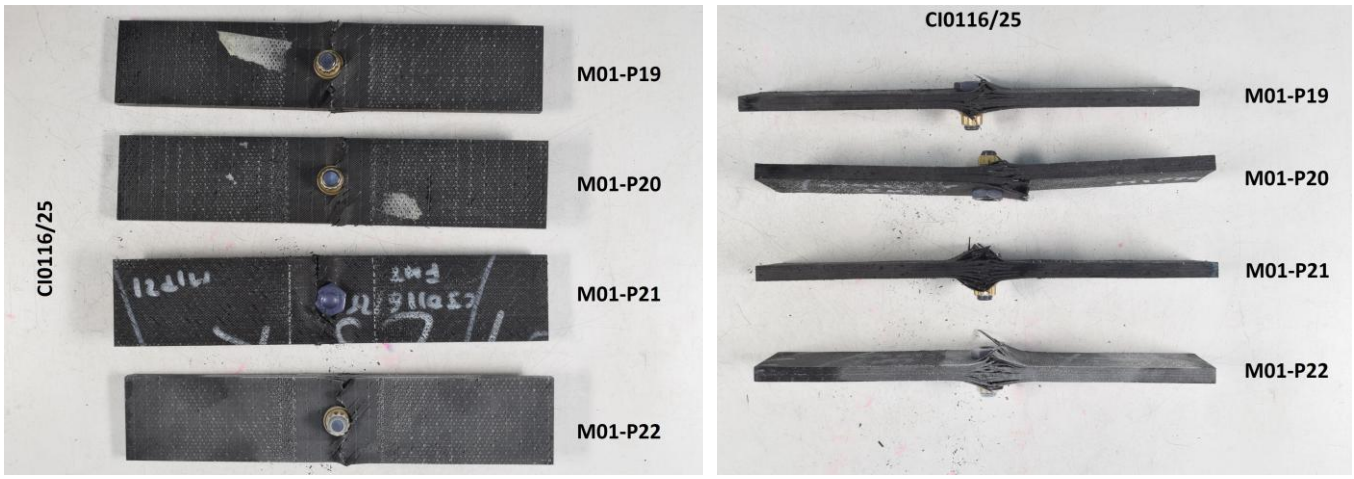

Figure 157. Failure mode for sensorised with microwires coupons – Batch 2. Compression tests (FHC), LT.

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Figure 158. Failure mode for sensorised with microwires coupons – Batch 3. Compression tests (FHC), LT.

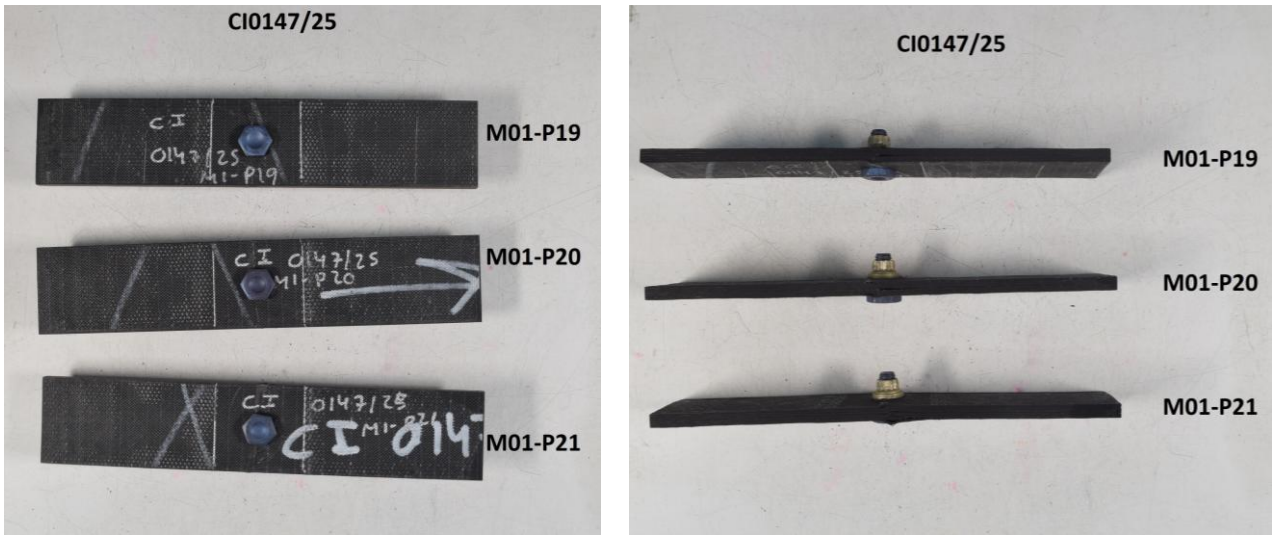

Figure 159. Failure mode for reference coupons – Batch 1. Compression tests (FHC), WET/RT.

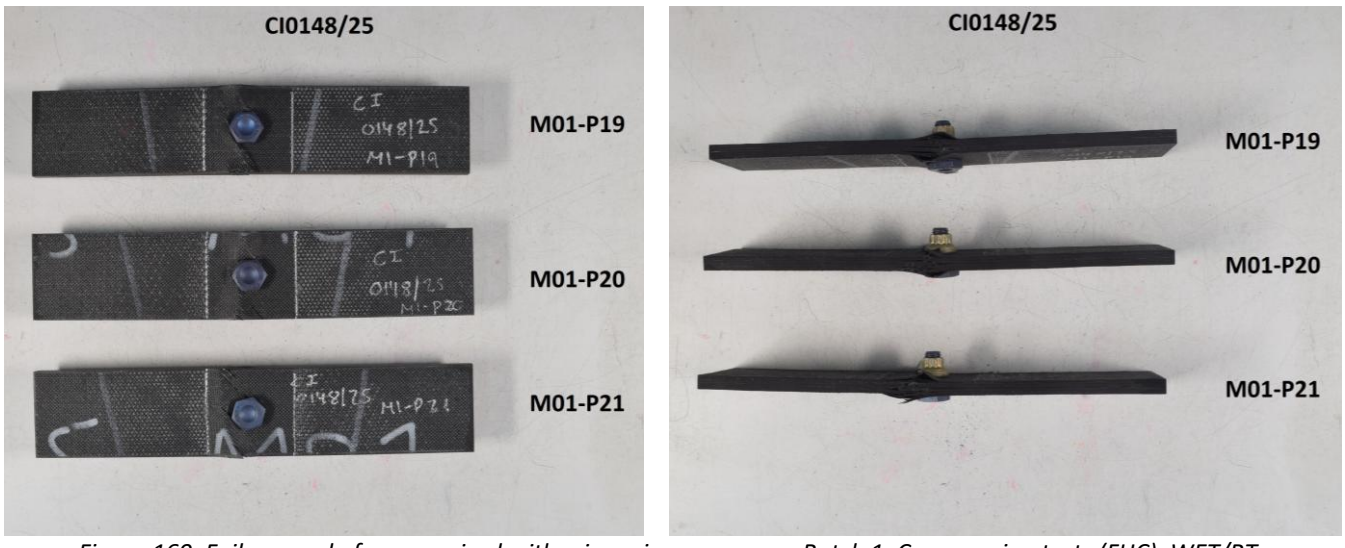

Figure 160. Failure mode for sensorised with microwires coupons – Batch 1. Compression tests (FHC), WET/RT.

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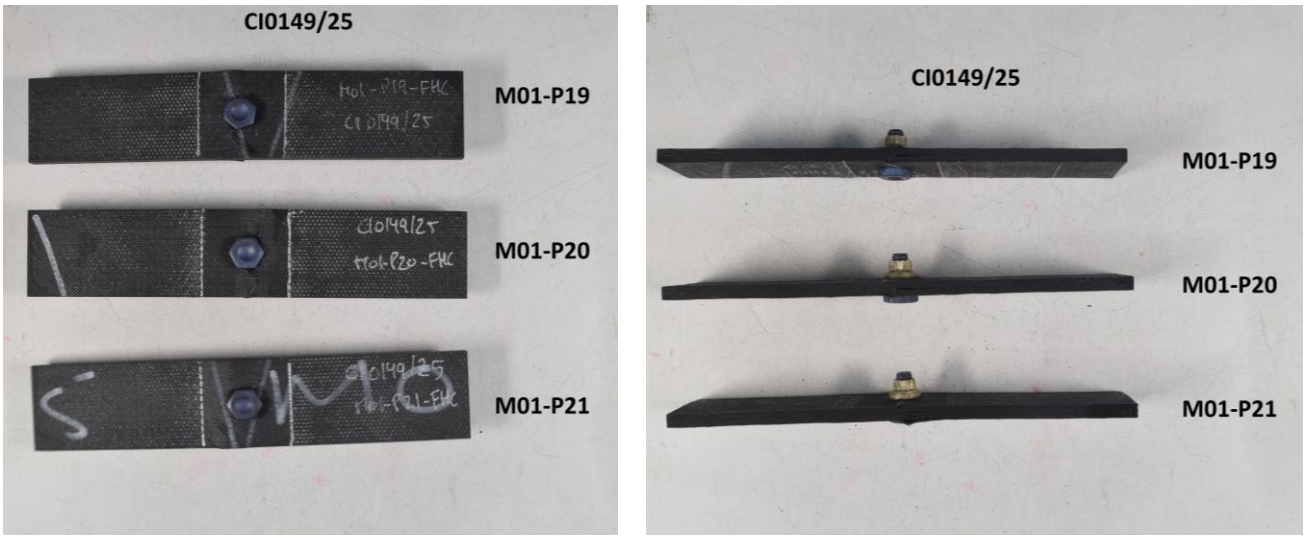

Figure 161. Failure mode for sensorised with microwires coupons – Batch 2. Compression tests (FHC), WET/RT.

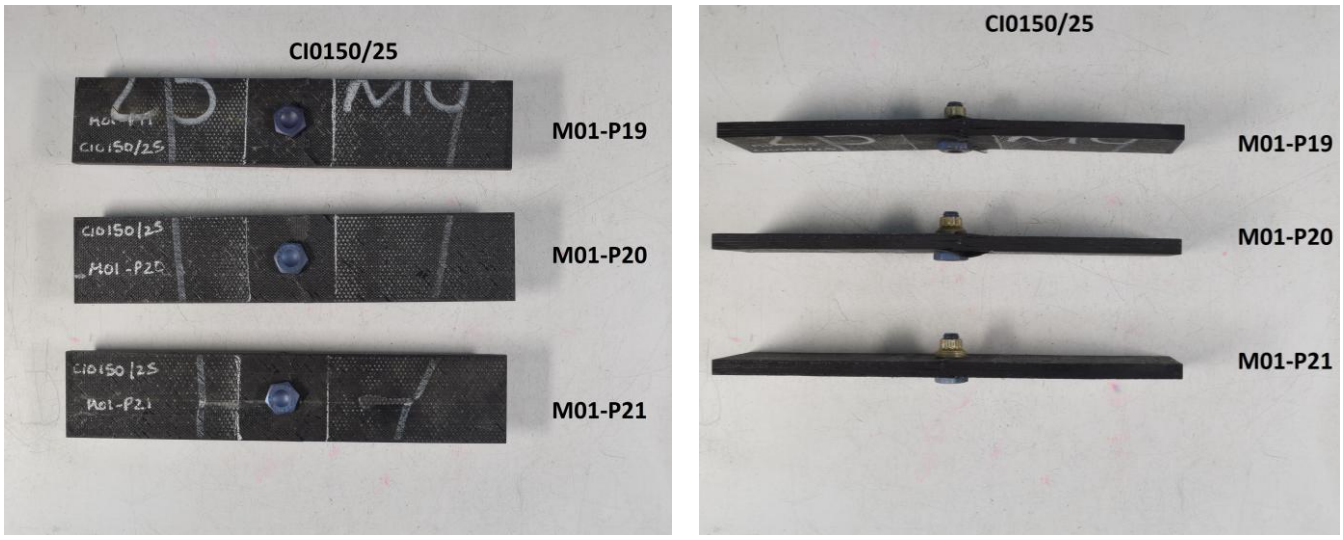

Figure 162. Failure mode for sensorised with microwires coupons – Batch 3. Compression tests (FHC), WET/RT.