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Mechanical comparison of new composite materials for aerospace applications

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Abstract: Composite materials are becoming the most useful material for aircraft structures. Their main advantage is connected to the possibility of deeply reducing weight and costs by maintaining high performances in terms of strength and security. The second major advantage of using this kind of material depends on the fact they could be proper designed to guarantee services they are made to. Many ways to combine them lead to the necessity of planning experimental tests in order to evaluate the real both elastic and plastic mechanical properties and to compare their variation as function of the fiber types, matrix types and manufacturing technology involved for realizing them. In this paper, a comparison between two innovative Carbon Fiber Reinforced Plastic materials was done. They differ, one from each other, for the matrix type (PEEK and BENZOXAZINE) and for the manufacturing process used to assemble the matrix with the reinforcement (Compression Molding and Resin Transfer Molding). On the other hand, the resin percentage weight content of both materials is maintained constant for all the tests: it is 42 % for PEEK matrix and 64 % for BENZOXAZINE matrix. The aim of the work is to critically analyze the results in order to get useful information for choosing the best one intended for designing and making the back section of fuselage of a regional aircraft. The component will consist of a front portion with structural aims (zoom phase) and a back part able to withstand to elevated temperatures.

Keywords: Carbon Fibers Reinforced Plastic (CFRP); experimental tests; mechanical properties

1. Introduction

Composite materials, intended as high-performance materials for engineering applications, are increasing in use in the last years [1]. They are non-homogeneous and anisotropic materials which require special consideration for determining physical and mechanical properties respect to metal ones [2]. The most important benefit respect to metal alloys is connected to the possibility of designing them *ad hoc* for the specific application they are intended to. This feature is strictly connected to the nature of composite materials. In fact, they consist at least of two separate phases which contributes together to the final properties: the reinforcement and the matrix. Differently from metallic materials, the “parts” of composites remain distinct from each other at the macroscopic level and are strongly affected by the damage mechanism of plies.

Several technological processes and lay-up distributions are considered for each particular application. The aim is to get the extreme structural exploitation of fibers matching the industrial requirements in terms of performances. The use of composite materials in aerospace field is representative of the elevated degree of complexity of mechanical design, because almost unlimited combinations of matrix and fiber patterns exist, but also because they could fail at not predictable loads neither by perfectly elastic nor perfectly plastic theories [3]. Consequently, experimental tests continue to play a significant role in the qualification process of new composite materials by using traditional [4] or hybrid techniques [5]. Aircraft structural design consists of various levels of structural testing, starting from specimen tests and finishing to full-scale structure tests [6]. For this reason, it becomes important to plan a full experimental campaign considering different kind of tests but also different kind of composite materials, in order to choose the proper combination material/lay-up ensuring the best outcomes.

Tensile and compression tests allow to evaluate the most representative properties of composite materials to be used in aircraft structures. Many of these tests must be arranged in a good experimental campaign. In general, the laws of deformation and failure of Carbon Fiber Reinforced Plastics (CFRP) are described adequately in many studies, generalized in handbooks and reviews [7-9]. Anyway, not many papers focus the attention on the analysis of mechanical response obtained by comparing composite materials made by the same kind of fibers combined with different matrix and/or different manufacturing technologies. The latter also depend on the nature of matrix (thermoset or thermoplastic), whose choice could deeply affect the final properties.

In this paper, a comparison between two CFRP has been carried out: CARBON/PEEK and CARBON/BENZOXAZINE. In particular, they are made by applying Compression Molding (CM) technology on the thermoplastic material, and Resin Transfer Molding (RTM) technology for the thermoset one. Tensile, compressive and open hole tensile tests have been carried out on specimens realized by using the two materials. The aim is to investigate the laws of deformation and failure of layered CFRP in order to define the better solution, in terms of performance required for the engineering industry [10], and especially for the aerospace one. Results getting from the experimental campaign will be used by the companies involved for validating the design phase of the back section of fuselage of a regional aircraft, consisting of a front portion with structural aims (zoom phase) and a back part able to withstand to elevated temperatures. These considerations limit the possibility of widely share the data, according to a Non-Disclosure Agreement (NDA) signed by all the companies and research centers involved.

2. Materials and Methods

Two innovative composite materials are experimentally tested. They are made as follows:

1. Carbon / PEEK (HTA40 - 5HS) hereinafter named *Material 1* – it is a laminate composite with thermoplastic matrix PEEK (density 1,30 g/cm^3) and High Tenacity carbon fibers - Density 1.76 g/cm^3 - with 3000 fibers per tow and "Five Harness Fabric" weaving; manufacturing technology - Compression Molding (Isothermal compression molding at 390 ° C and 20 bar).
2. Carbon / BENZOXAZINE (5HS HTA40 / BZ9110) hereinafter named *Material 2* - it is a laminate composite with thermosetting matrix BENZOXAZINE BZ9110 (density 1,22 g/cm^3) and High Tenacity carbon fibers - Density 1.76 g/cm^3 - with 12000 fibers per tow and "Five Harness Fabric" weaving; manufacturing technology - Resin Transfer Molding (resin injection at 110 ° C and 8 bar, and curing treatment for 90 minutes at 180 ° C).

The table below shows the properties of both materials (Tab. 1).

Table 1. Material properties of 2 CFRP

MATERIAL PROPERTIES	Fiber	Tensile Strength [MPa]	Tensile Modulus [GPa]	Filament diameter [µm]	Density [g/cm^3]	Matrix	Number of fiber per tow	Manufacturing Technology	Weaving
Material 1	TENAX HTA-40	3950	238	7,0	1,76	Thermoplastic PEEK	3000	Compression Molding (CM)	5HS
Material 2	TENAX HTA-40	3950	238	7,0	1,76	Thermosetting BENZOXAZINE BZ9110	12000	Resin Transfer Molding (RTM)	5HS

CM is a reliable manufacturing process that uses metal molds with the application of external pressure. In the compression molding process, an engineered composite lay-up is placed in the open mold cavity, and when it is closed a consolidating force is applied. The pressure was continuously kept constant during the whole cure cycle, occurring in an oven. The combination of heat and pressure produces a composite part with low voids content and high fibers volume fraction, whose finishing surface is similar to a net shape. Compression molding can yield composite parts having the optimal mechanical properties possible depending on the combination of constituent phases. This type of molding process allows to manufacture complex geometries components (e. g. holes) without requiring machined post-mold processes. This technique produces good integrated composite structure (carbon fiber, aramid fiber or fiberglass) needing of fewer knit lines and lower fiber-length degradation respect to the injection molding.

RTM is an increasingly used type of molding, mainly applied to mold components having large surfaces, complex shapes and smooth finishes. It is a low pressure closed molding process for low volume production. It represents a compromise between the slower contact molding processes and the faster compression molding process, which requires high tooling costs. Continuous strand mats and woven reinforcement are laid dry in the mold bottom half. The mold is clamped, and a low viscosity resin is pumped with the aim of pushing put the air. Common matrix resins include polyester, vinyl ester, epoxy, and phenolics. Advantages respect to contact molding methods are connected to the possibility of obtaining uniform thickness, two finished sides and low emissions. For optimum surface finishing, a gel coat would be applied to the mold surface prior to molding. High quality parts produced by this method include automotive body parts, bathtubs, and containers.

Experimental campaign consists in testing 40 specimens carried out by using the two different CRFP materials. Specimens obtained by the two materials were subjected to three types of mechanical tests, in order to determine tensile, compression and open-hole tensile properties. All tests were performed by using a 250 kN servo-hydraulic testing machine, with hydraulic clamping.

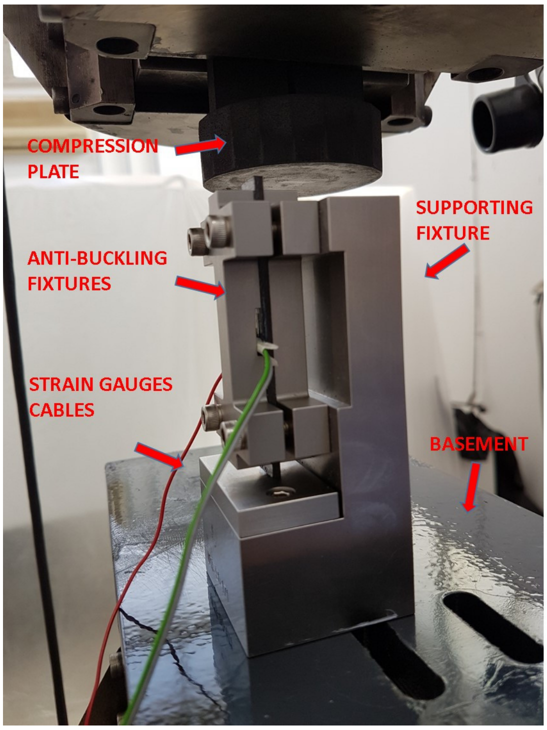


Figure 1. Compression Modulus: Test Setup

Tensile tests were performed according to standard ASTM D3039 [11]. Five specimens of *Material 1* and five of *Material 2* were tested at a constant crosshead displacement equal to 2 mm/min. *Material 1* laminate consists of 8 plies assembled according to $[(0,90)_4]_s$ lay-up. *Material 2* laminate consists of 6 plies assembled according to $[(0,90)_3]_s$ lay-up. All the tested specimens were cut at 0 ° respect to the load direction. Specimens were long 250 mm and had a rectangular cross-section for both materials. In particular, the section had dimensions 25 mm x 2,48 mm for *Material 1* and 25 mm x 2,35 for *Material 2*. The different thicknesses are connected to the standard requirements. Their difference doesn't affect the test results because the resin percentage weight content for both materials is maintained constant for all the tests: it is 42 % for PEEK matrix and 64 % for BENZOXAZINE matrix. The specimens were clamped in testing machine by using resins tabs according to the standard suggestions [11]. Two strain gauges for each side were applied on specimens to monitor strain behavior. On each side, one was positioned half-way axially and the second was applied transversely, according to the standard [11].

Compression tests were performed according to SACMA SRM-1 [12]. Ten specimens for each material were tested at a constant crosshead displacement equal to 1 mm/min. Five were cut at 0 ° and five at 90 ° respect to the load direction. For both the materials, the number of plies was 8 and the laminate lay-up was assembled according to [(0,90)4]s scheme. Specimens were long 80 mm and had a rectangular cross-section for both materials. In particular, the section had sizes 15 mm x 2,48 mm for Material 1 and 15 mm x 3,04 mm for Material 2. A standard loading system was used. It was an anti-buckling compression system positioned between two flat surfaces firmly connected to the testing machine grips (Fig. 1). In order to define the compression modulus one strain gauge (1.5 mm base, 350 Ohm) was positioned at the middle section of test samples which didn't have any tabs [12].

Open hole tensile tests were carried out in accordance with ASTM D5766/D5766M [13]. Five specimens of each material have been tested at a constant crosshead displacement equal to 2 mm/min. (Fig. 2). They were cut at 0° respect to the load direction and had the same lay-up $[(0,90)_4]_s$. Specimens were long 200 mm and had a rectangular cross-section holed at the middle-length for both materials. In particular, the section had sizes 36 mm x 2,48 mm for *Material 1* and 36 mm x 3,04 mm for *Material 2.* All the holes had a 6 mm diameter in order to respect the suggested standard ratios D/h (diameter/thickness) between 1,5 and 3, and w/D (width/diameter) equal to 6.

All test specimens have a size and geometry according to indications provided by the corresponding standard.

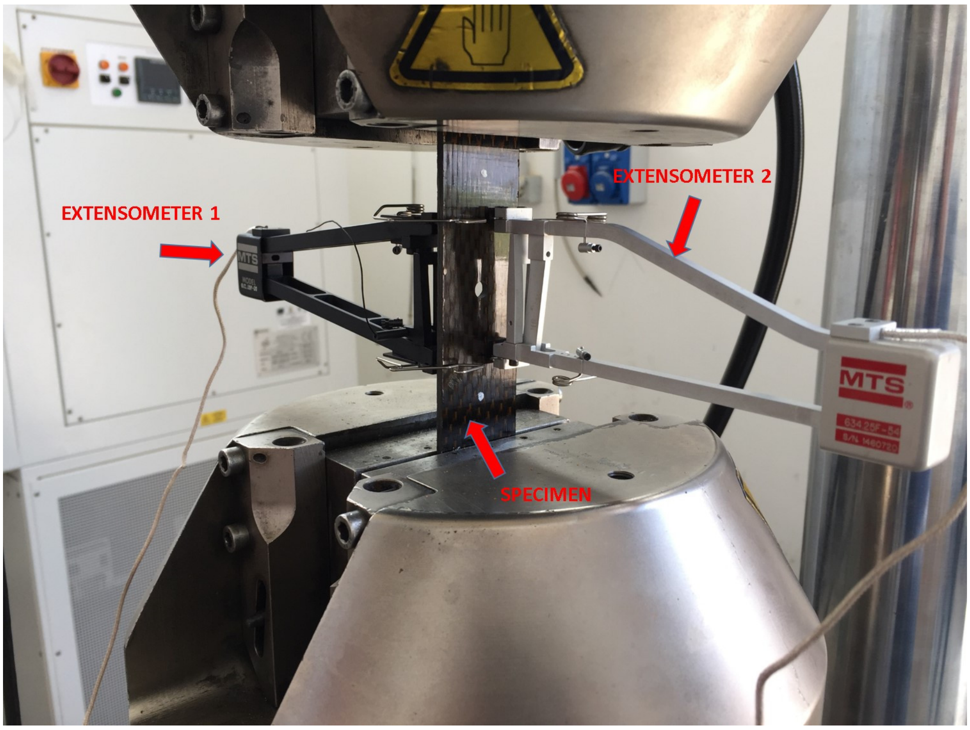


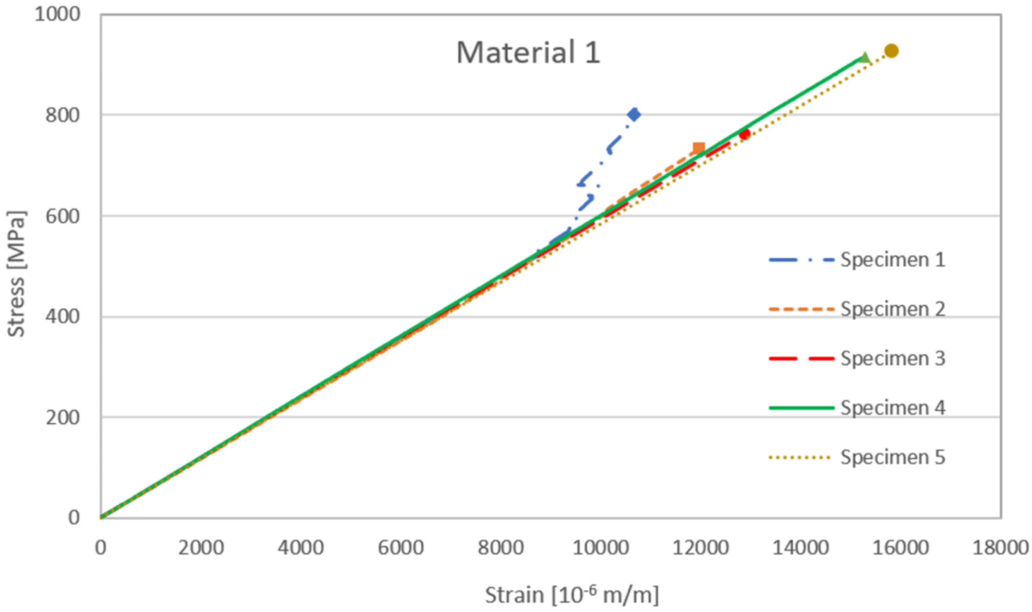
Figure 2. Open Hole Tensile: Test Setup

3. Results

Results obtained are critically compared according to the specific test they refer to in order to define the best material for the specific purpose.

Figure 3 reports the complete test evolution of the five samples of each material in order to observe the repeatability of the tests.

Figure 4 and 5 show a graphical comparison of the two CFRP subjected to tensile load. They report the stress-strain behavior of one representative sample of each material and the mean value of elastic properties of both them. It is possible to observe that: the ultimate tensile strength as well as the Poisson ratio are higher for *Material 1* than *Material 2*, conversely the Young modulus is slightly greater for *Material 2* than *Material 1*.



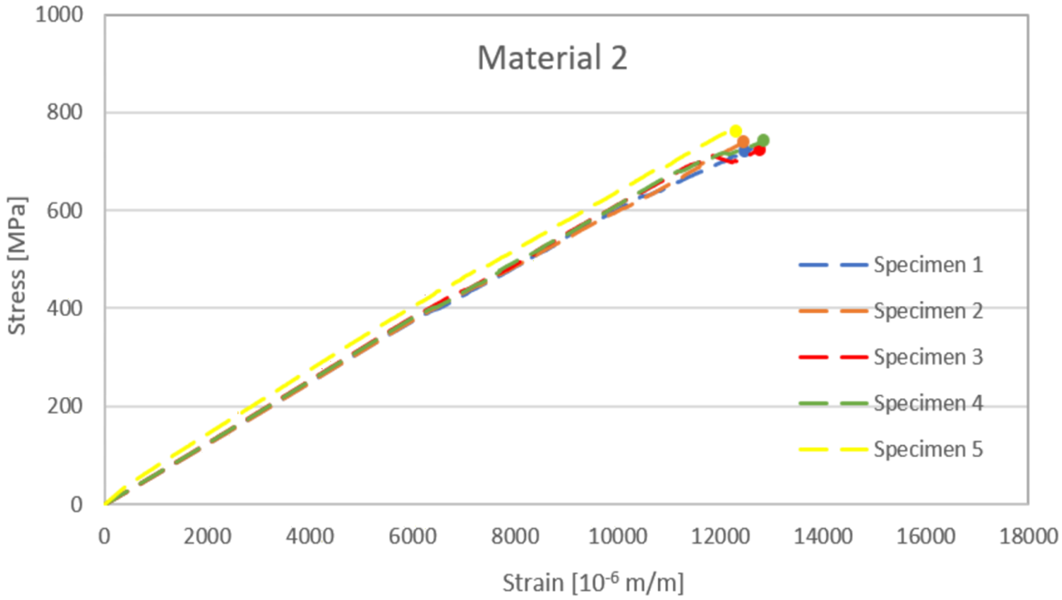


Figure 3. Tensile trends of *Material 1* and *Material 2*

These results seem to asses that the type of resin affects the elastic properties (E) and alternatively the manufacturing process influences the plastic properties (σ). Generally, it is known that the thermosetting resins (*Material 2*) is characterized by higher resistance and hardness than the thermoplastic ones (*Material 1*), as confirmed by [14]. Namely *Material 1* is more ductile than *2*, that is to say it has a lower Young modulus and at the same time a higher Poisson ratio by combining a higher rate of transversal contraction with a less pronounced longitudinal elongation. On the other hand, the unexpected attitude of ultimate tensile strength could be explained only by considering the different manufacturing process of composite laminates. As previously described, in fact, the *Material 1* was obtained by using a CM process, while the *Material 2* was realized by means of RTM. The main difference between them refers to the pressure level of processes. RTM involves only low pressure during the injection which helps in obtaining more uniform components and thus inducing high mechanical strength [10].

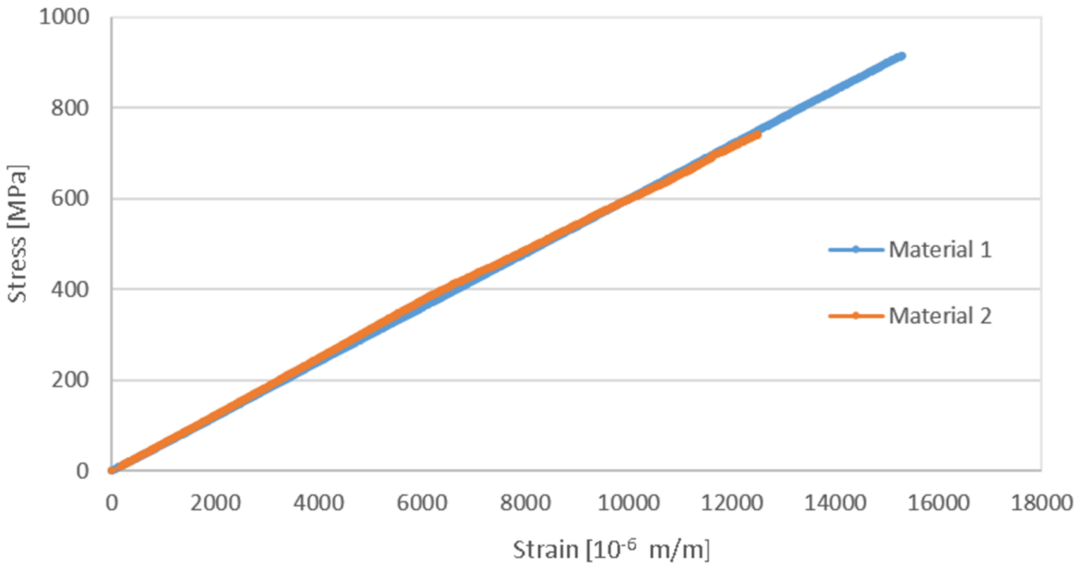


Figure 4. Tensile Test: Graphical comparison

In order to better shows the differences between both materials, the numerical values of tensile results are reported in Table 2. All values indicate the error and the percentage difference of *Material 1* respect to *Material 2* too.

Table 2. Numerical results of tensile tests

TENSILE TEST	**Maximum Tensile Stress [MPa]**	**Young Modulus [MPa]**	**Poisson's Ratio**
Material 1	898,3 ± 51,9	59790 ± 576	0,073 ± 0,010
Material 2	739,8 ± 15,7	62949 ± 589	0,059 ± 0,004
Error (%) 1 over 2	21%	5%	24%

The mode and the location of failure of all the specimens are reported in Figure 6 and 7. The predominant type of failure is codified as Lateral (L) At grip/tab (A) Top (T) or Bottom (B) for both materials, according to the standard typical modes [11]. Another observation concerns with the percentage type of failures for both materials: it seems that *Material 1* predominant failure is located at top or at the bottom of the specimen (4 specimens over 5 show LAT or LAB failure), on the other hand for *Material 2* the predominant one is located at the gage section (5 specimens over 5 show a breakage in correspondence of the middle section).

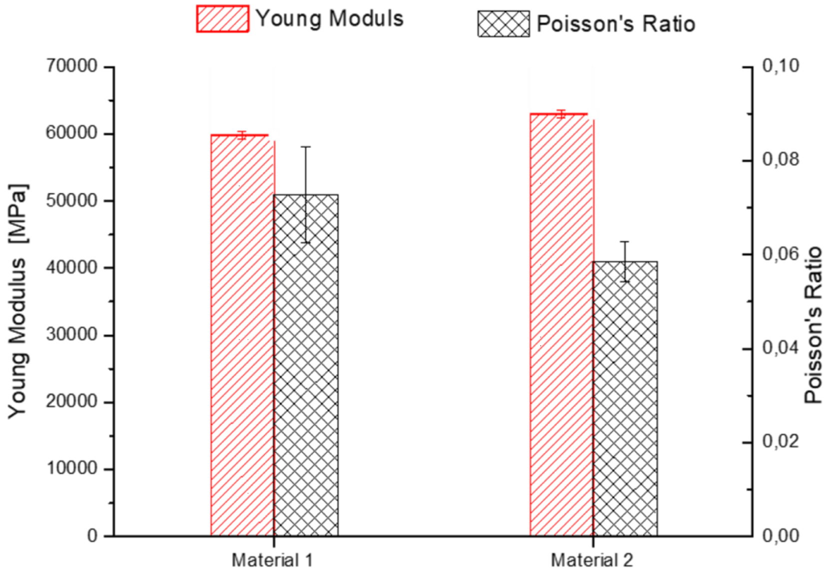


Figure 5. Tensile Test: Mechanical Properties Comparison

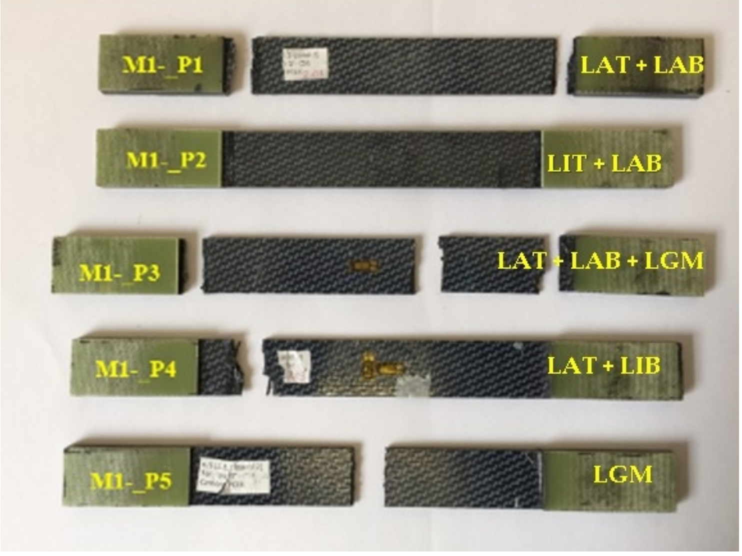


Figure 6. Tensile Test: Carbon/PEEK failure modes of specimens

Looking at the compression tests, the stress-strain trend seems to be quite similar for both materials (Fig. 8 e 9). Anyway, by analyzing the compressive moduli, it is possible to note that a perfect isotropic behavior is accounted only for *Material 1*, despite *Material 2* (Fig. 10). The difference of modulus values is neglectable in the first case and is about 6000 MPa for the second one. This unforeseen result suggests a higher compressive stiffness in 90° respect to 0°, indicating the presence of some effects able to improve the mechanical strength only in one direction, even if the laminate is balanced and symmetric. Considering the phases composition of two materials, the only difference between them is connected to the type of matrix and manufacturing process.

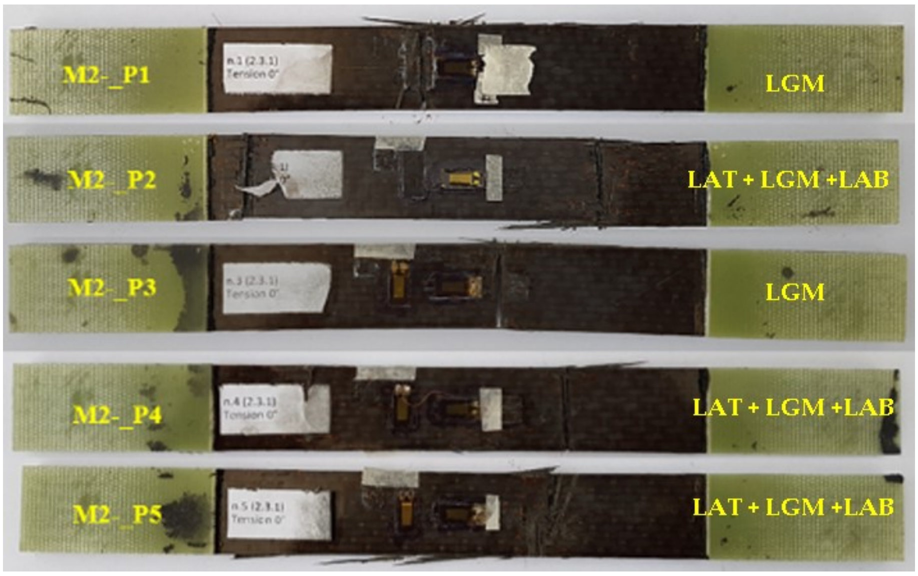


Figure 7. Tensile Test: Carbon/Benzoxazine failure modes of specimens

Another important consideration refers to the comparable values of compressive and tensile moduli of both CFRP materials. According to the scientific literature, the basic assumption of CFRP tape is based on the statistics that compressive modulus is fraction lower than the tensile one [15]. This attitude is disproved for CFRP fabric. In particular, by using a Five Harness Satin Fabric it is possible to improve the compressive properties up to the tensile one, ensuring better performances for specific purpose.

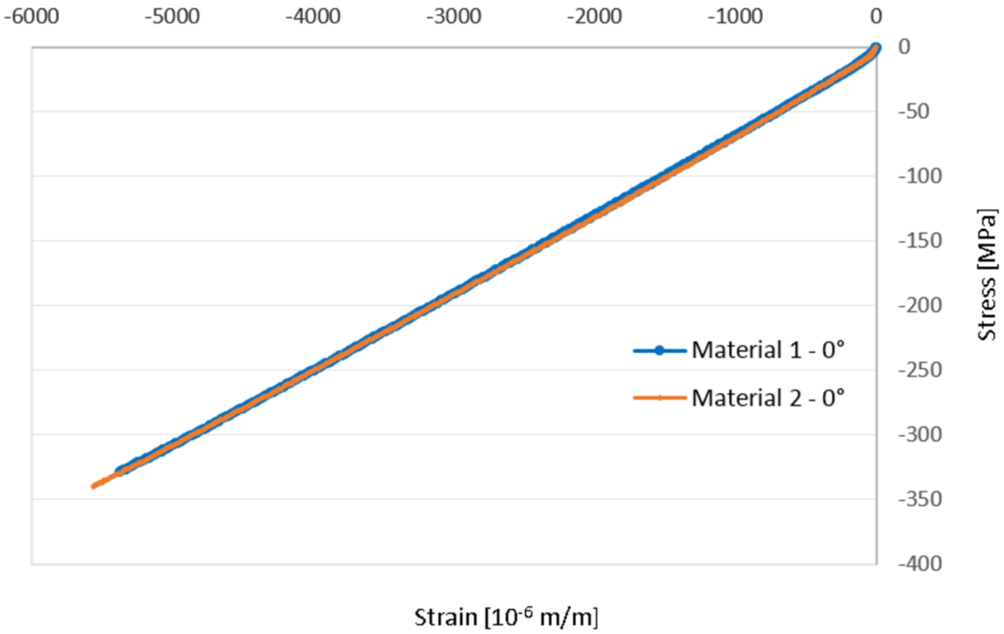


Figure 8. Compression Test 0°: Graphical Comparison

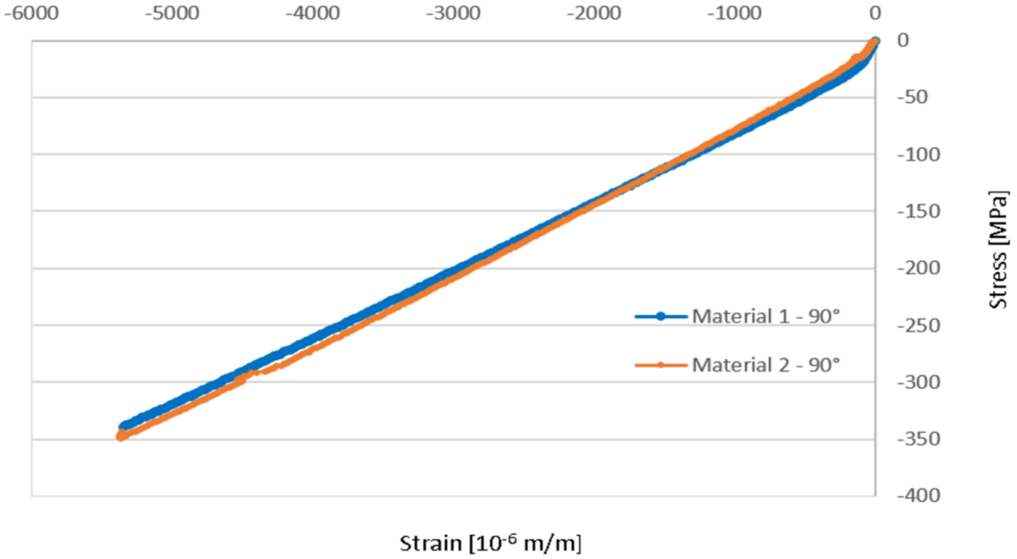


Figure 9. Compression Test 90°: Graphical Comparison

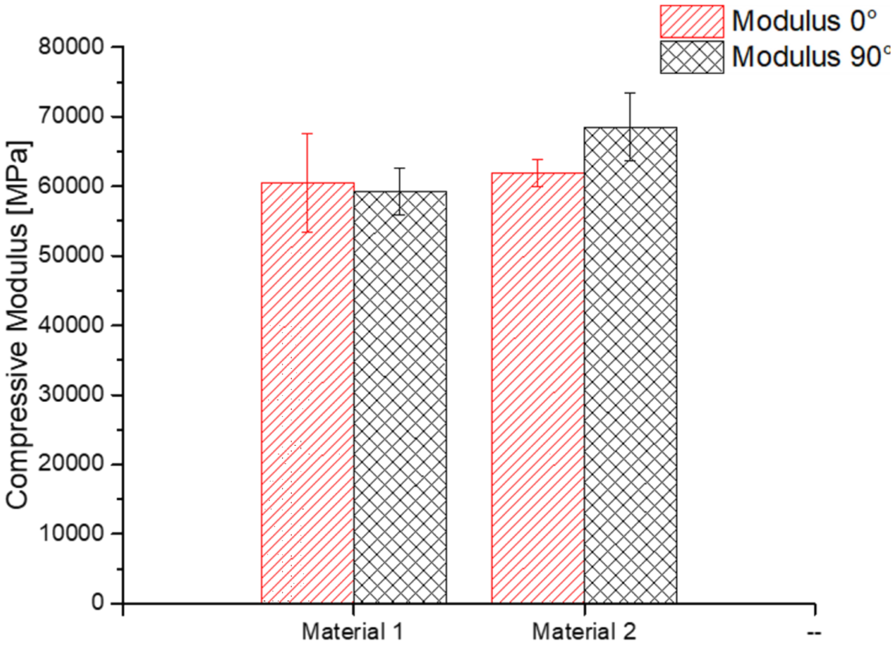


Figure 10. Compression Test: Modulus Comparison

In order to better shows the differences between both materials, the numerical values of compressive results are reported in Table 3. All values indicate the error and the percentage difference of *Material 1* respect to *Material 2* too.

The type of failure of all the specimens are reported in Figure 11 and 12. The characteristic type of failure is a crush localized indifferently at up or bottom terminal edge of the specimens for both materials.

Table 3. Numerical results of compressive tests

COMPRESSIVE MODULUS TEST	Compressive Modulus 0° [MPa]	Compressive Modulus 90° [MPa]
Material 1	60415 ± 7377	59099 ± 3654
Material 2	61797 ± 2009	68325 ± 4686
Error (%) 1 over 2	2%	14%

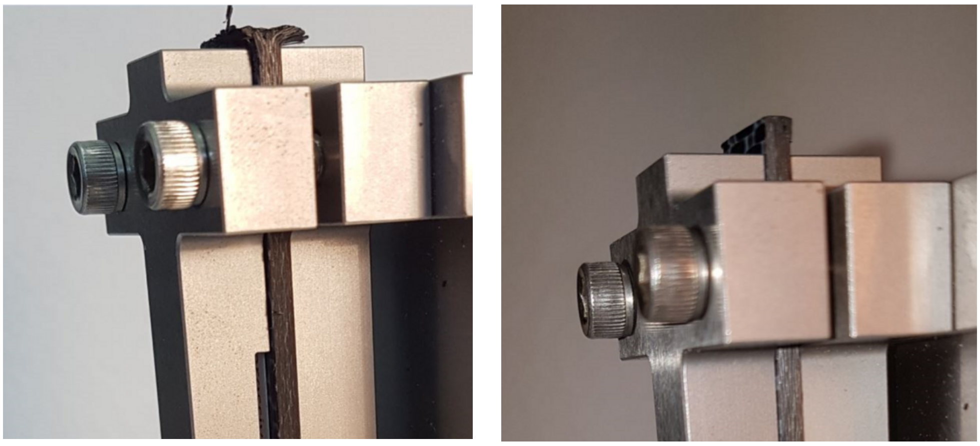


Figure 11. Compression Test: Carbon/PEEK failure modes of specimens 0° and 90°

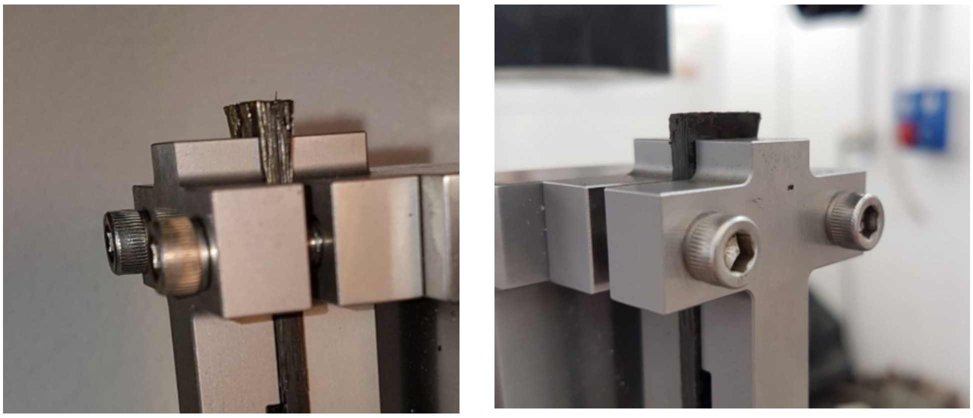


Figure 12. Compression Test: Carbon/Benzoxazine failure modes of specimens 0° and 90°

Finally, open hole tensile results are compared (Fig. 13). Due to the presence of the hole tensile strength and decreases: comparison of samples, characterized by the same lay-up and design parameters but without holes, indicates that a decreasing of 53% for *Material 1* and of 31% for *Material 2* in ultimate tensile strength happens. The percentage decreasing, between unnotched and notched samples have been commonly observed by many researchers [– 16-17].

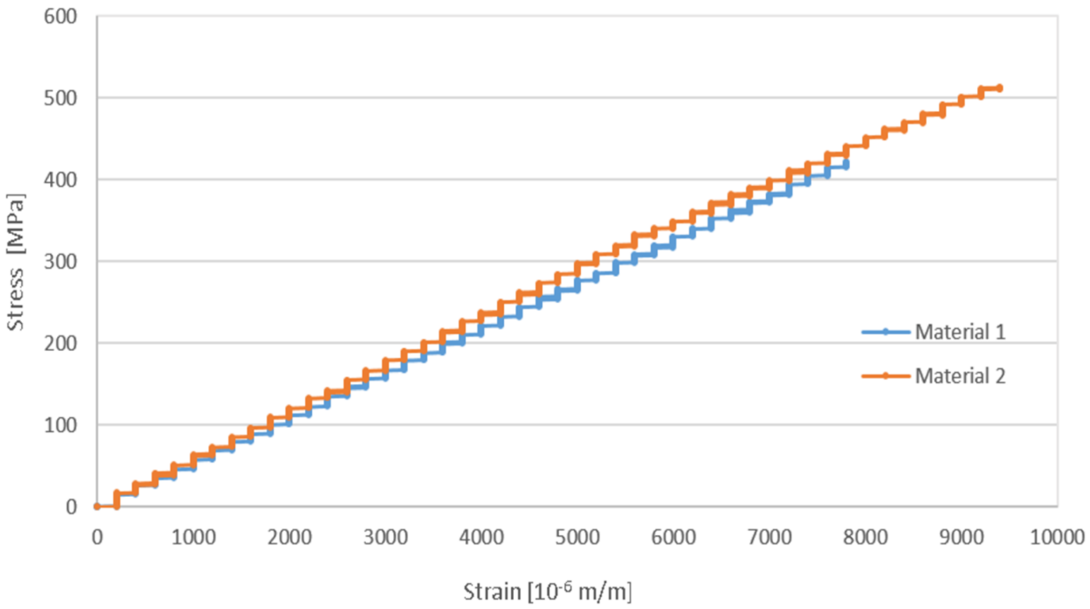


Figure 13. Open Hole Tensile Test : Graphical comparison

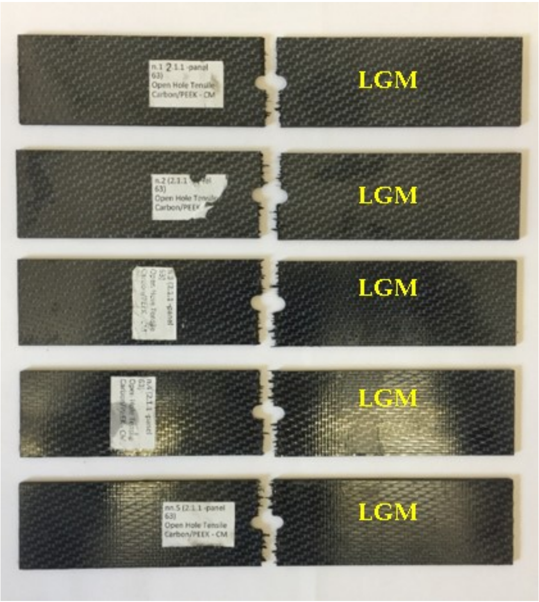


Figure 14. Open Hole Tensile Test: Carbon/PEEK failure modes of specimens

By comparing the two CFRP materials the main aspect that need to be underlined refers to the different effects the hole has in the mechanical strength. It results, in fact, that the ultimate open hole tensile strength of *Material 1* is lower than *Material 2*, and this is in contrast with the results obtained in ultimate tensile strength. It seems that the hole manufacturing largely affects the mechanical properties, by reducing the composite strength according with the resin nature.

In order to better shows the differences between both materials, the numerical values of open-hole tensile results are reported in Table 4. All values indicate the error and the percentage difference of *Material 1* respect to *Material 2* too.

Table4. Numerical results of open-hole tensile tests

OPEN-HOLE TEST	Ultimate Open-Hole Strength (MPa)	Young Modulus (MPa)
Material 1	431,9 ± 14	56926 ± 1481
Material 2	508,8 ± 8,7	57540 ± 1133
Error (%) 1 over 2	18%	1%

The type of failure of all the specimens are reported in Figure 14 and 15. The predominant type of failure is codified as Lateral (L) Gage (G) Middle (M), according to the standard typical modes [13].

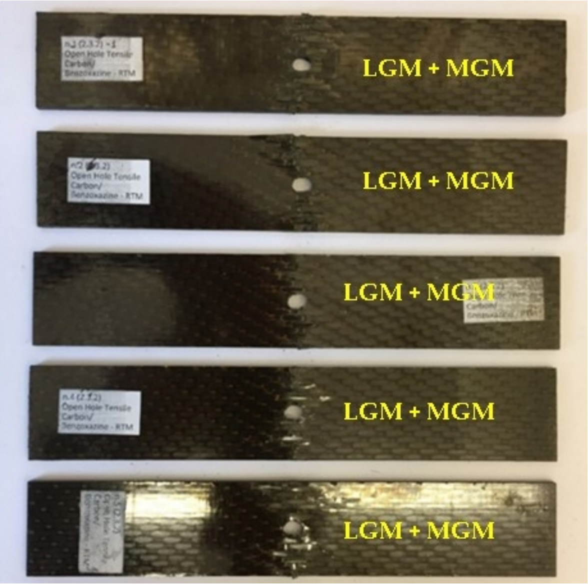


Figure 15. Open Hole Tensile Test: Carbon/Benzoxazine failure modes of specimens

4. Conclusions

In this paper, a comparison of two CFRP materials was carried out. They were built by combining the same fibers with two types of resin and two manufacturing processes. Three kinds of experimental tests were planned to aim at defining the better combination materials/manufacturing process: tensile, compressive and open-hole tensile tests. Results seems to show some beneficial effects on mechanical tensile properties due to the technological process. Despite the expected behavior due to the thermosetting matrix, the ultimate tensile strength as well as the Poisson ratio are higher for *Material 1* than *Material 2*. The type of resin affects only the elastic properties (E).

On the other hand, the manufacturing methods appear to differently affect the compressive behavior of symmetric and balanced composites along two different load directions. The results suggest a higher compressive stiffness in 90° respect to 0° for *Material 2*, indicating the presence of some beneficial effects of RTM process able to improve the mechanical strength only in one direction, even if the laminate is balanced and symmetric.

Then open tensile tests didn’t show any influences of technological process respect to the real properties of composite resins. It seems that the hole manufacturing largely affects the mechanical properties, by reducing the composite strength according with the resin nature.

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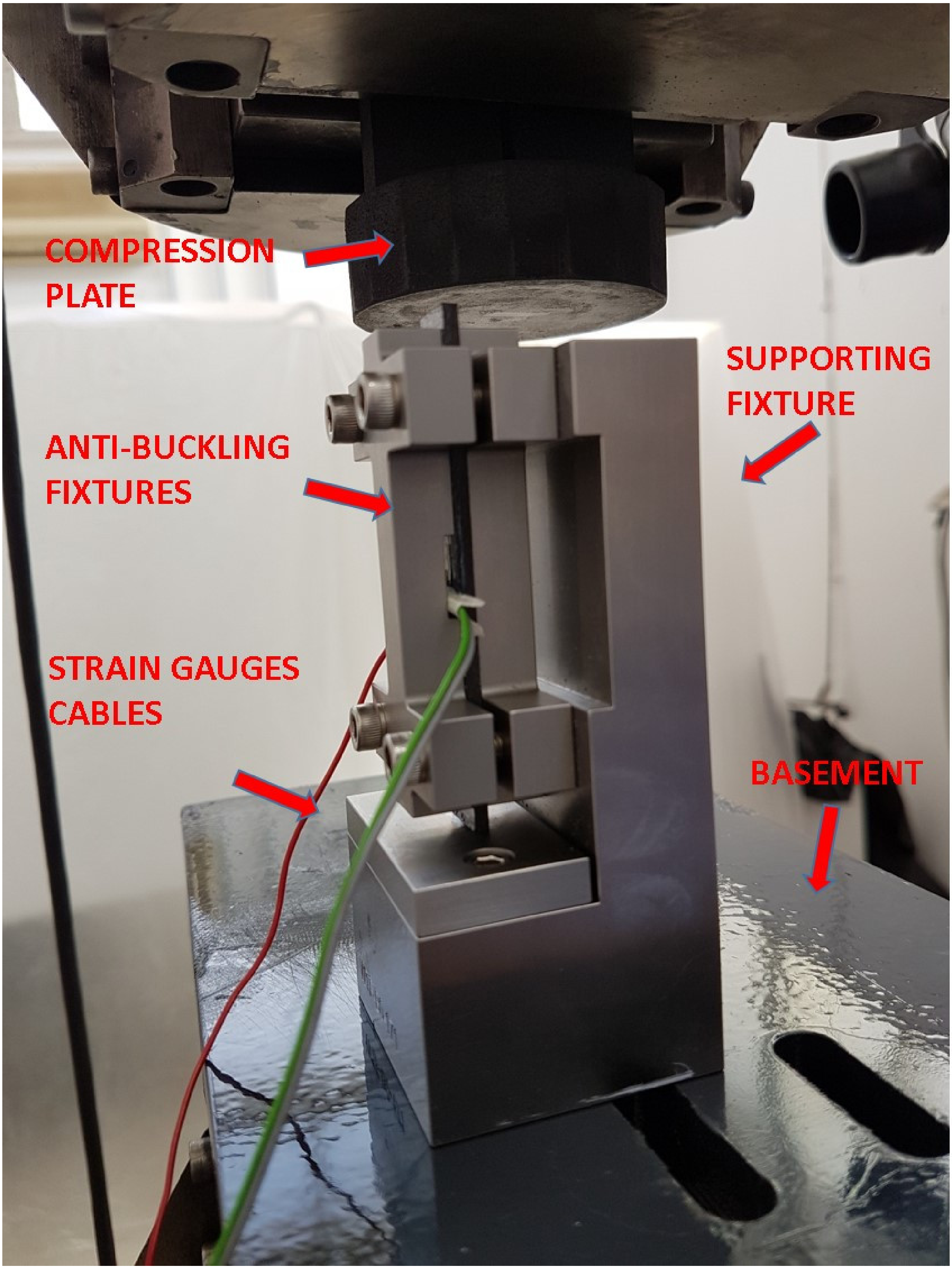
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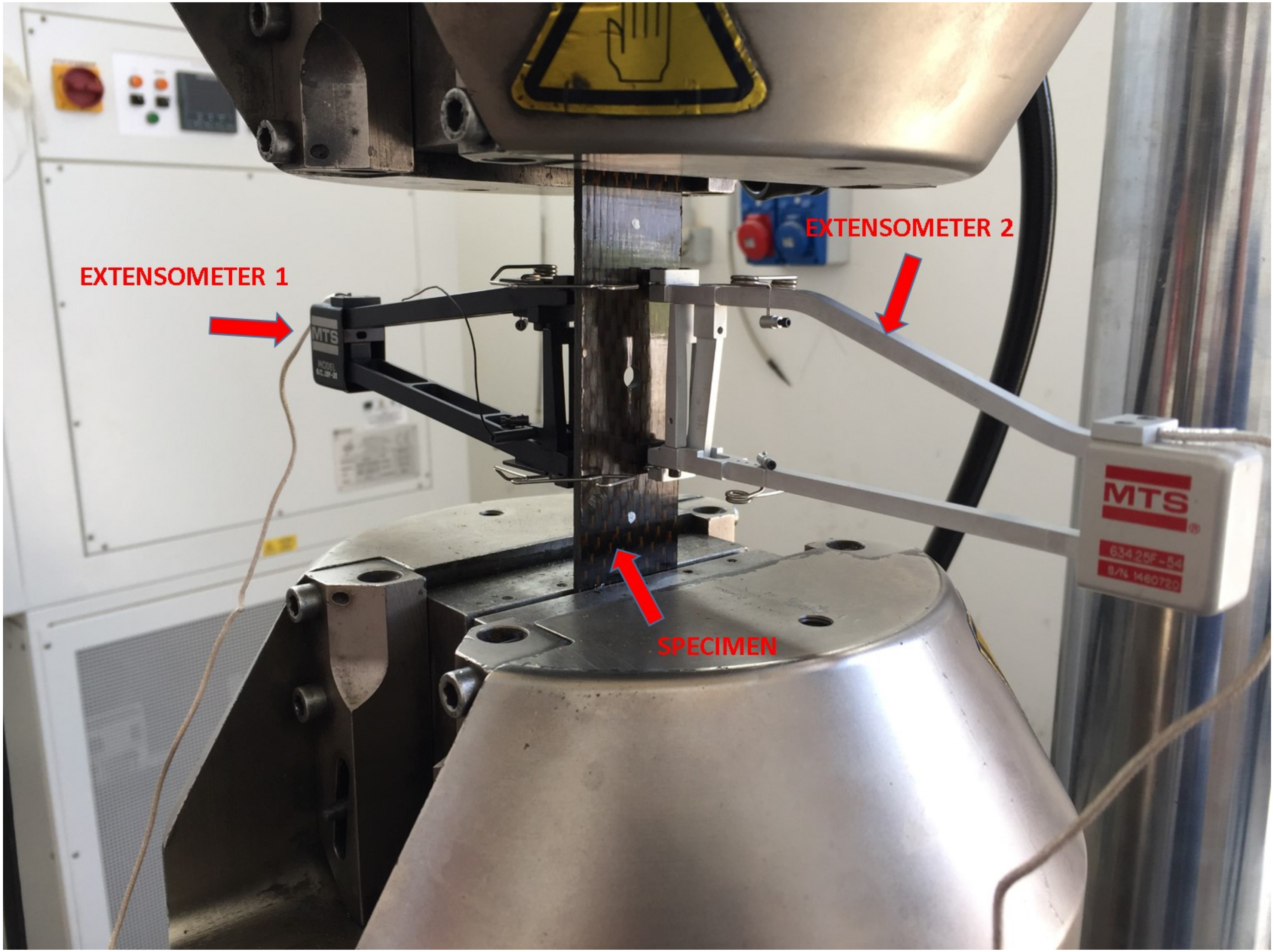
SUPPORTING FIXTURE
ANTI-BUCKLING FIXTURES
STRAIN GAUGES CABLES
BASEMENT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EXTENSOMETER 2
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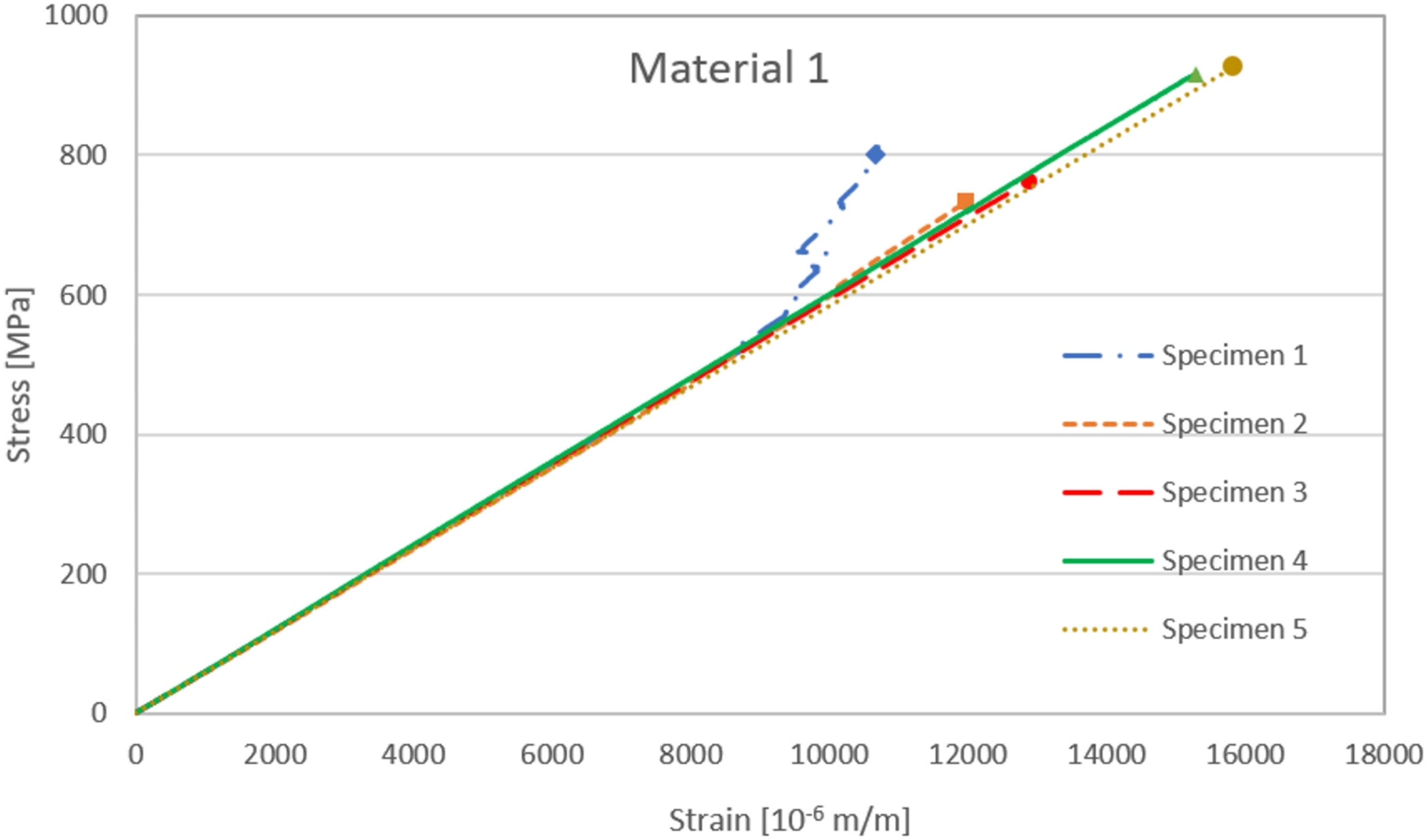
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Stress [MPa]
1000
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0
2000
4000
6000
8000
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Strain [10⁻⁶ m/m]
Specimen 1
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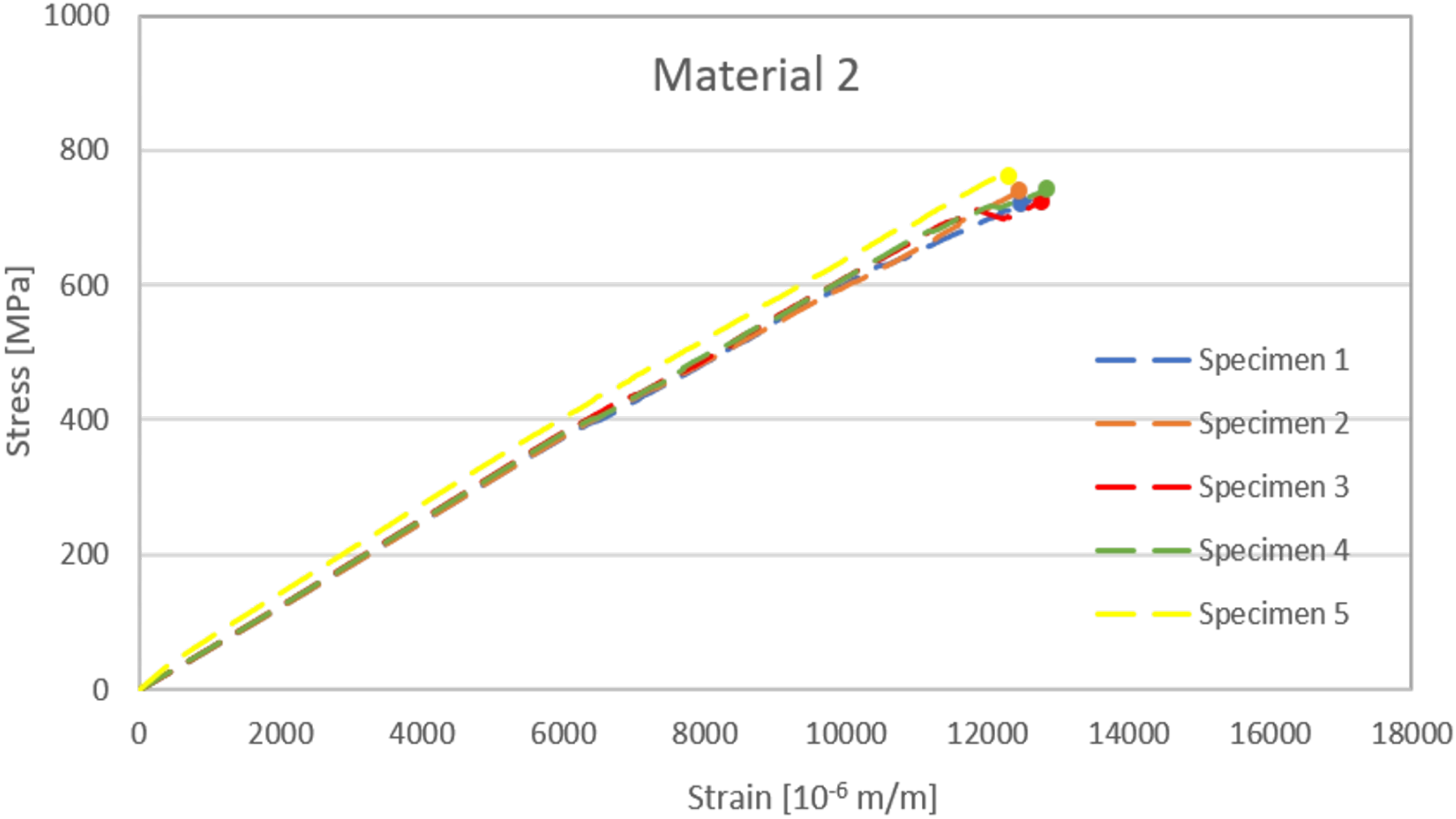
Material 2
Stress [MPa]
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800
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Strain [10⁻⁶ m/m]
0
2000
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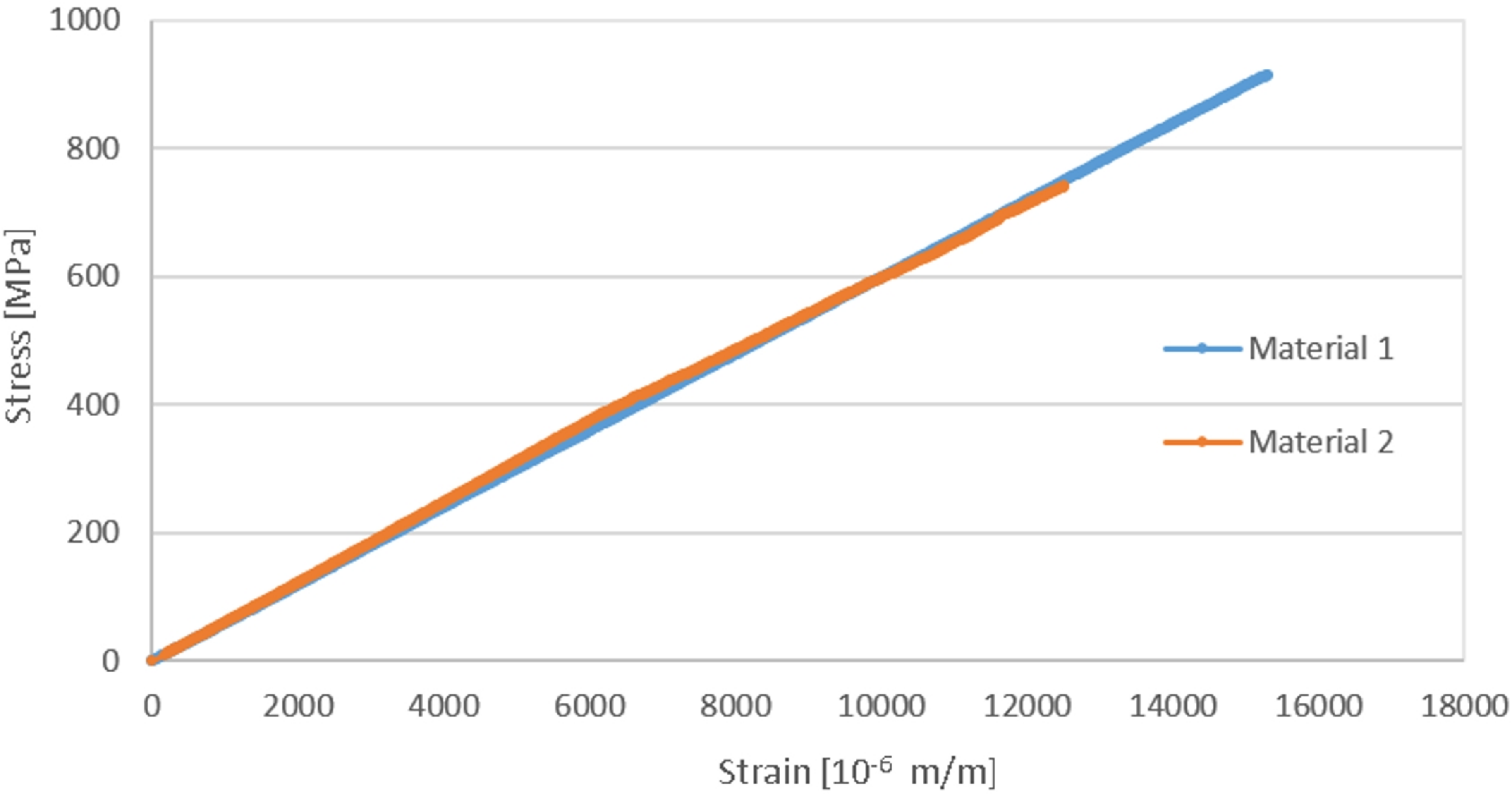
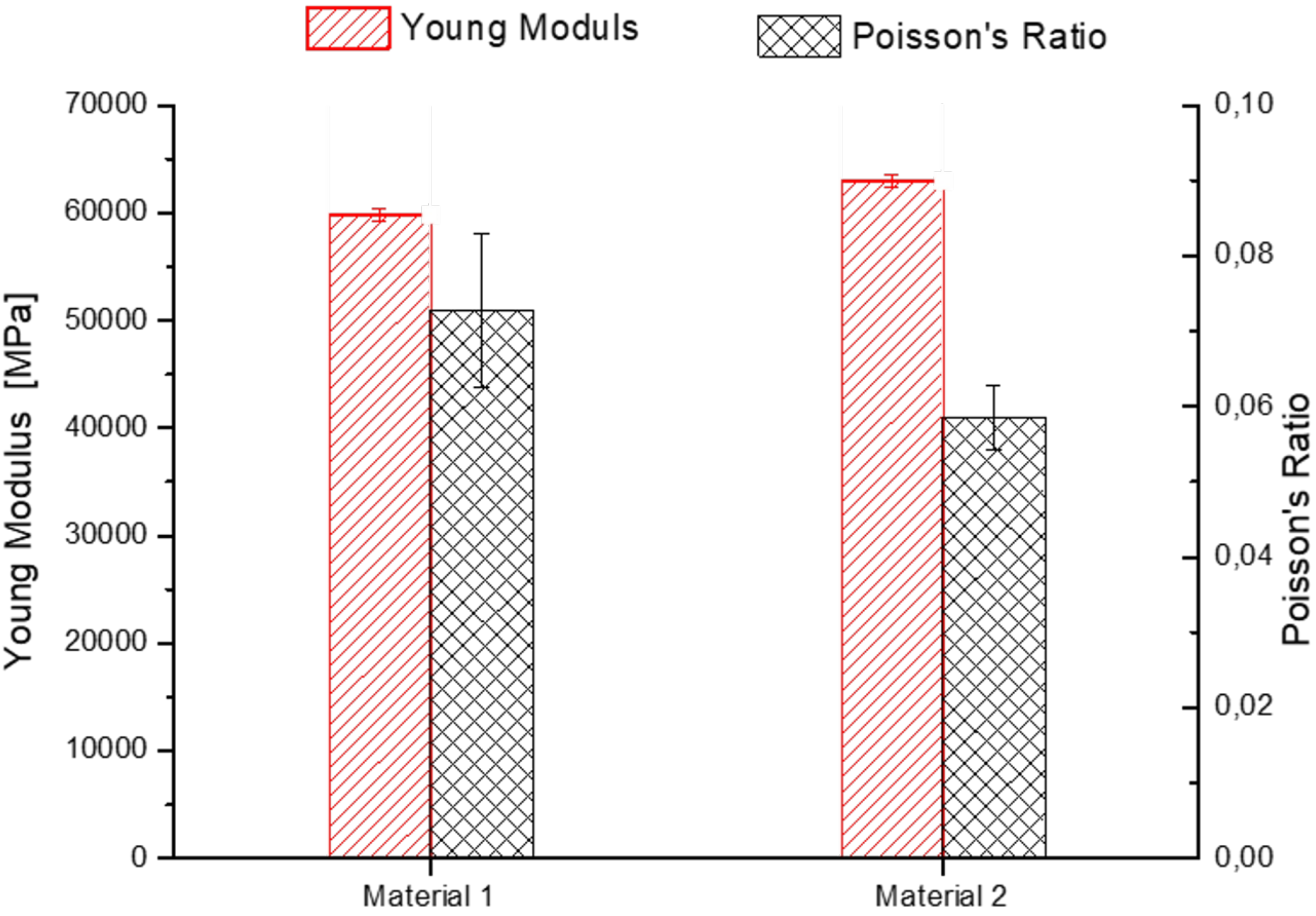
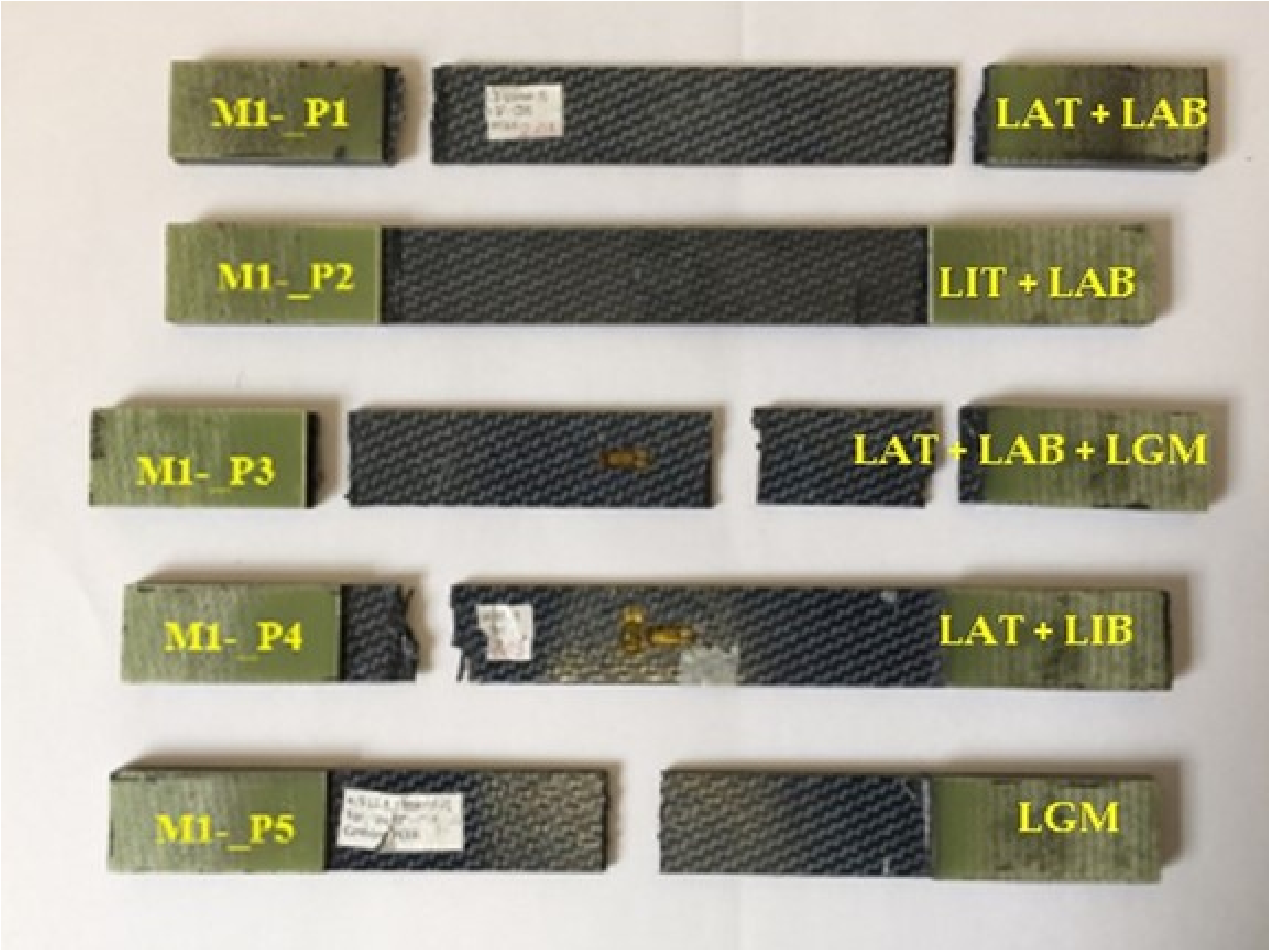
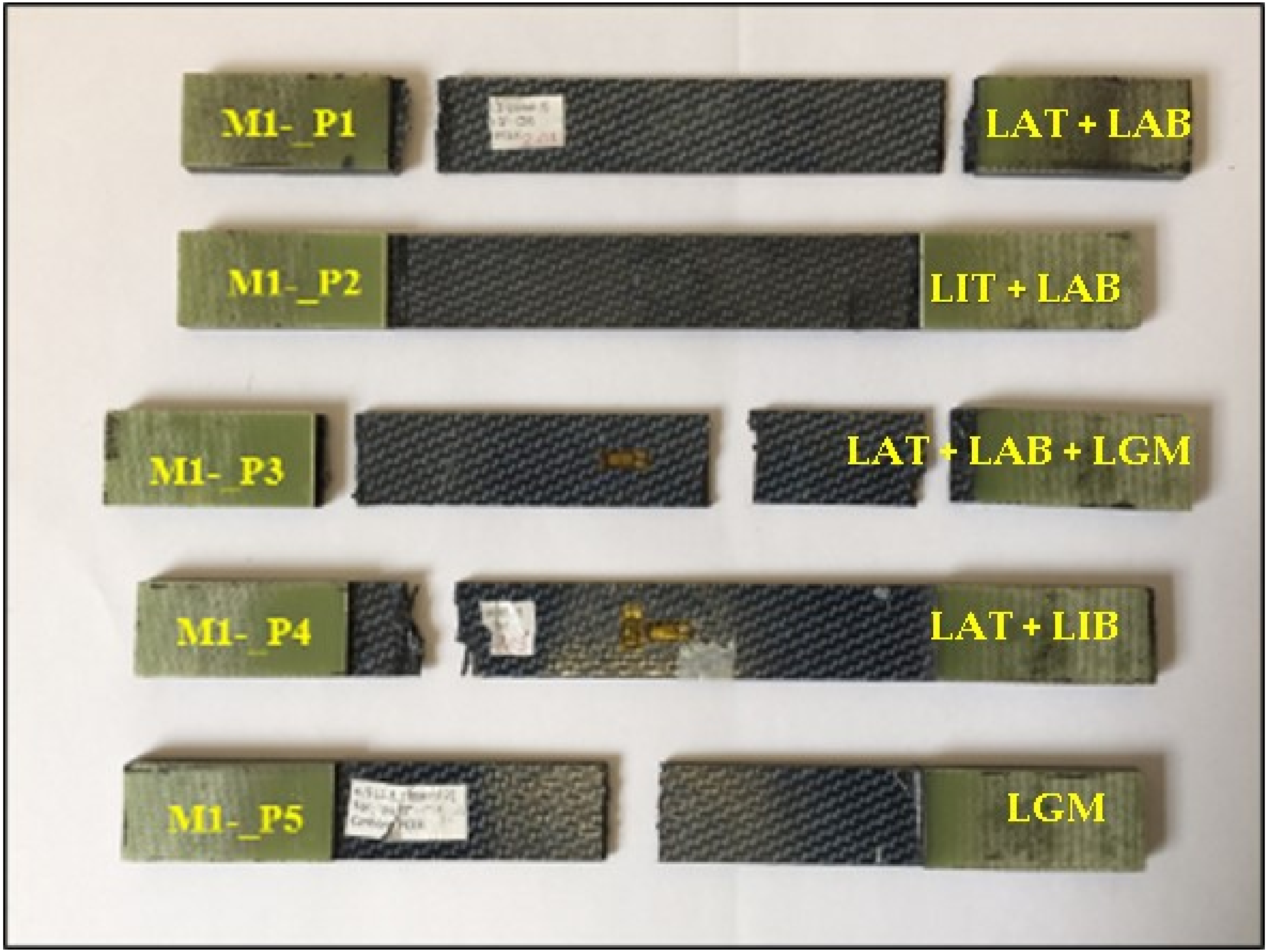
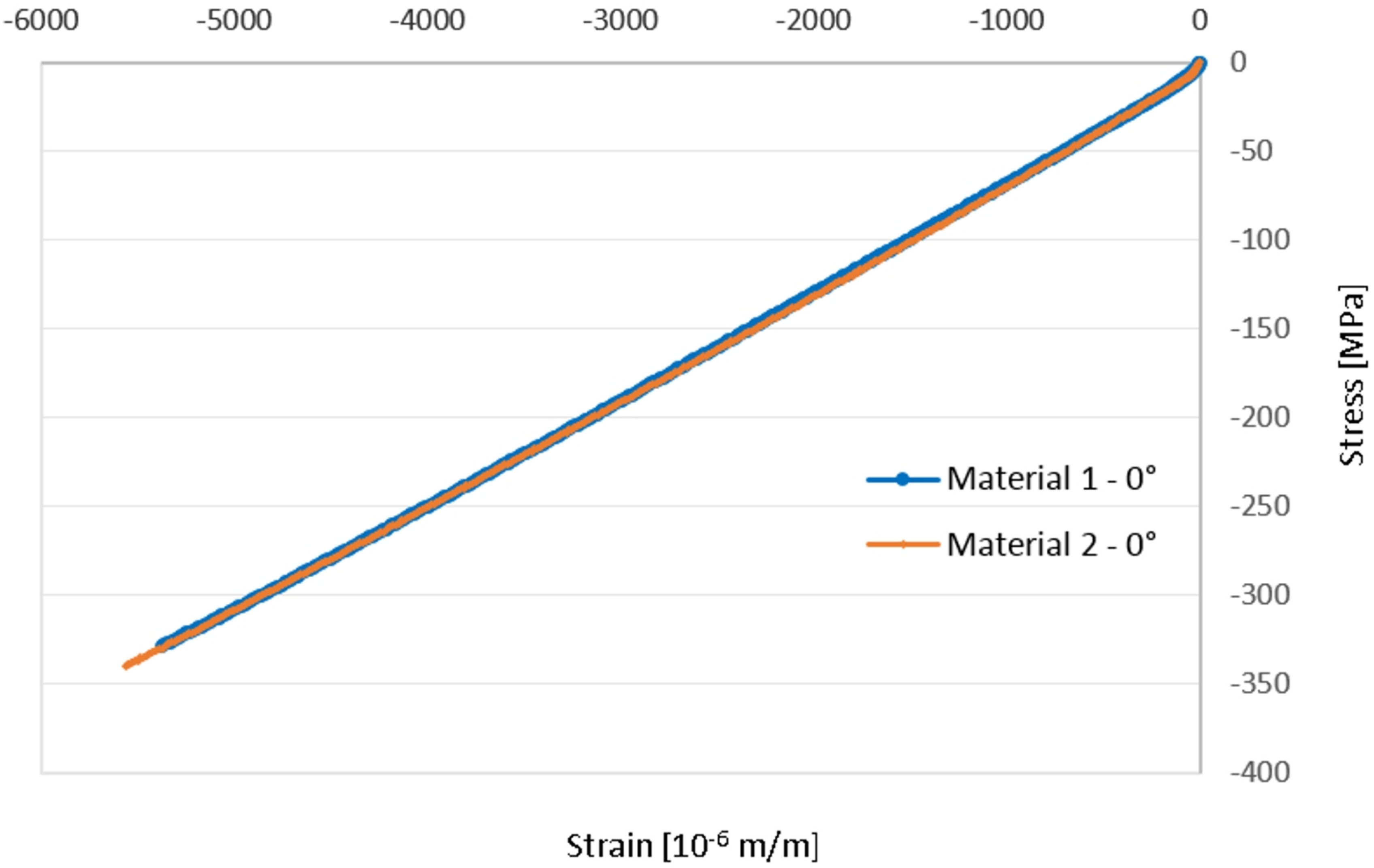
Specimen 4
Specimen 5

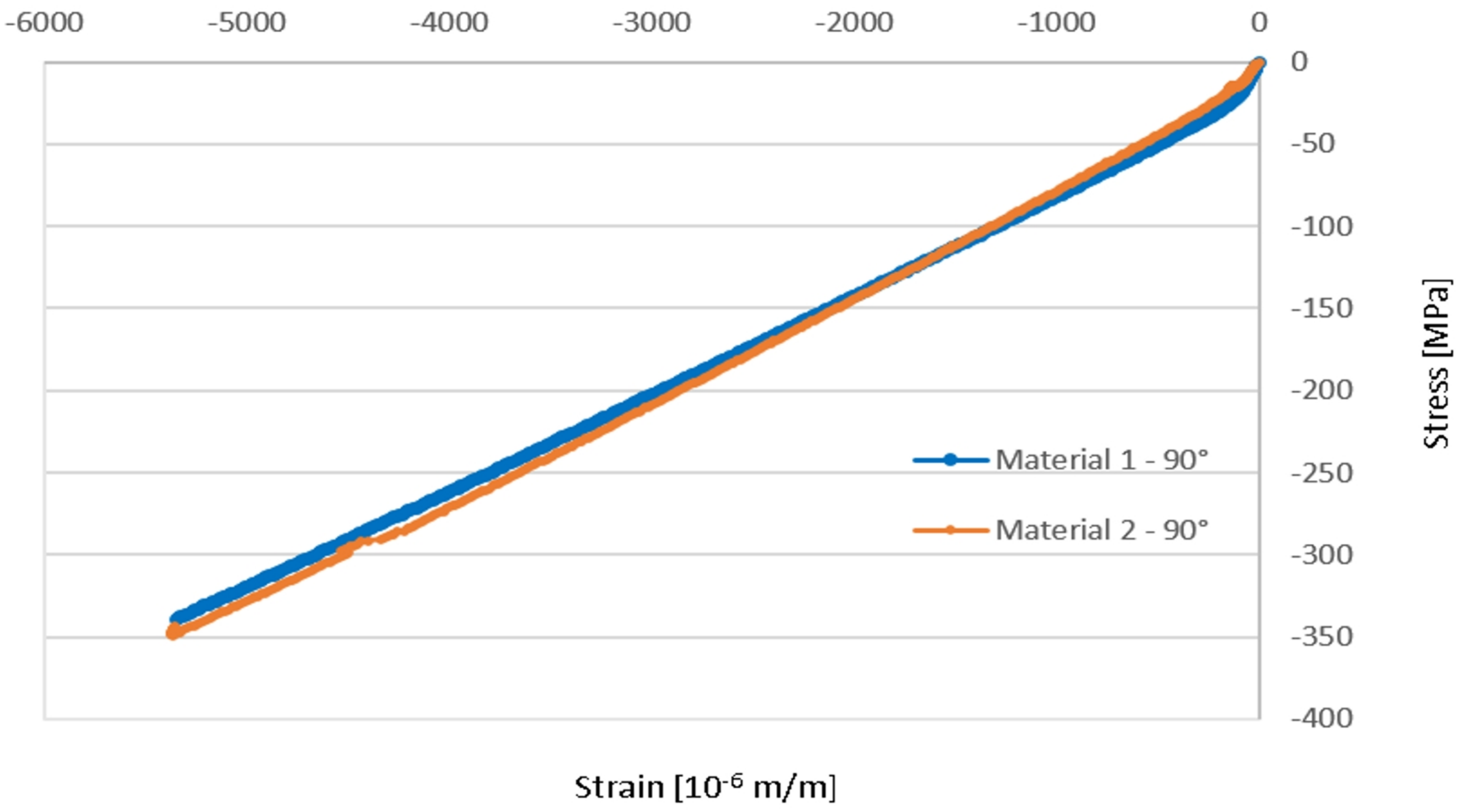

1000
800
600
400
200
0
Stress [MPa]
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
Strain [10^{-6} m/m]
Material 1
Material 2

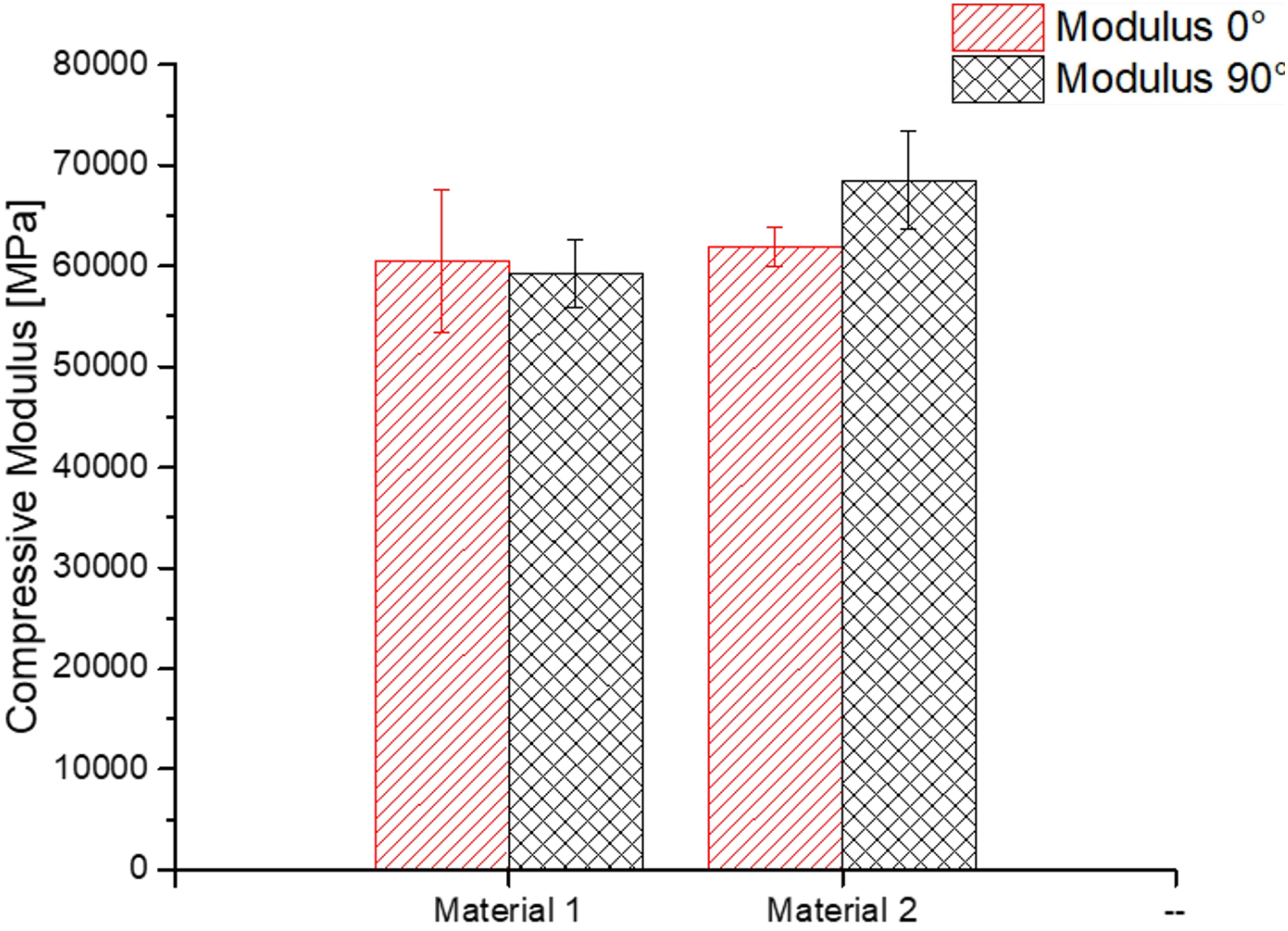

Young Moduls
Poisson's Ratio
Young Modulus [MPa]
70000
60000
50000
40000
30000
20000
10000
0
Poisson's Ratio
0,10
0,08
0,06
0,04
0,02
0,00
Material 1
Material 2

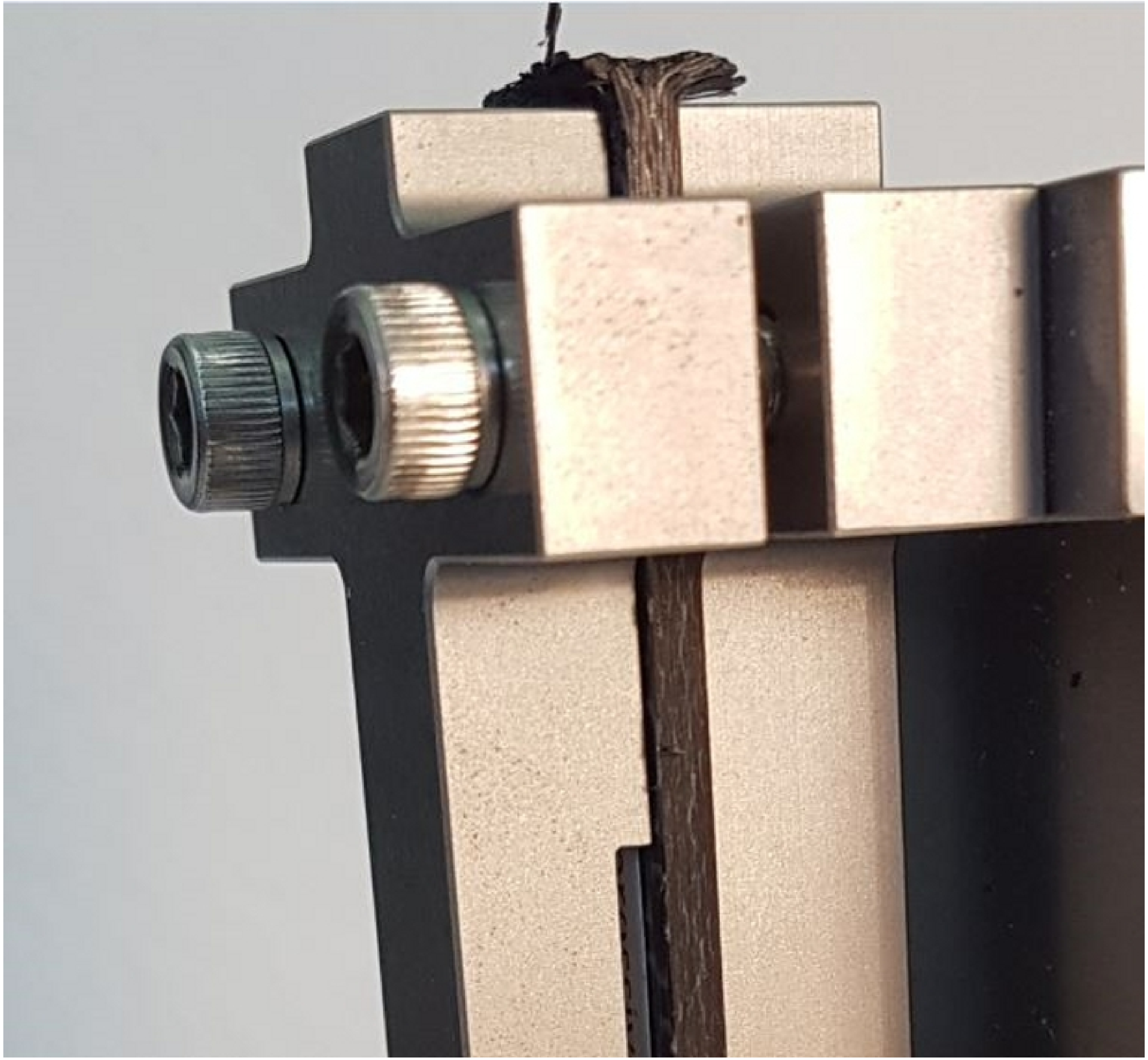

M1-_P1
LAT + LAB
M1-_P2
LIT + LAB
M1-_P3
LAT + LAB + LGM
M1-_P4
LAT + LIB
M1-_P5
LGM

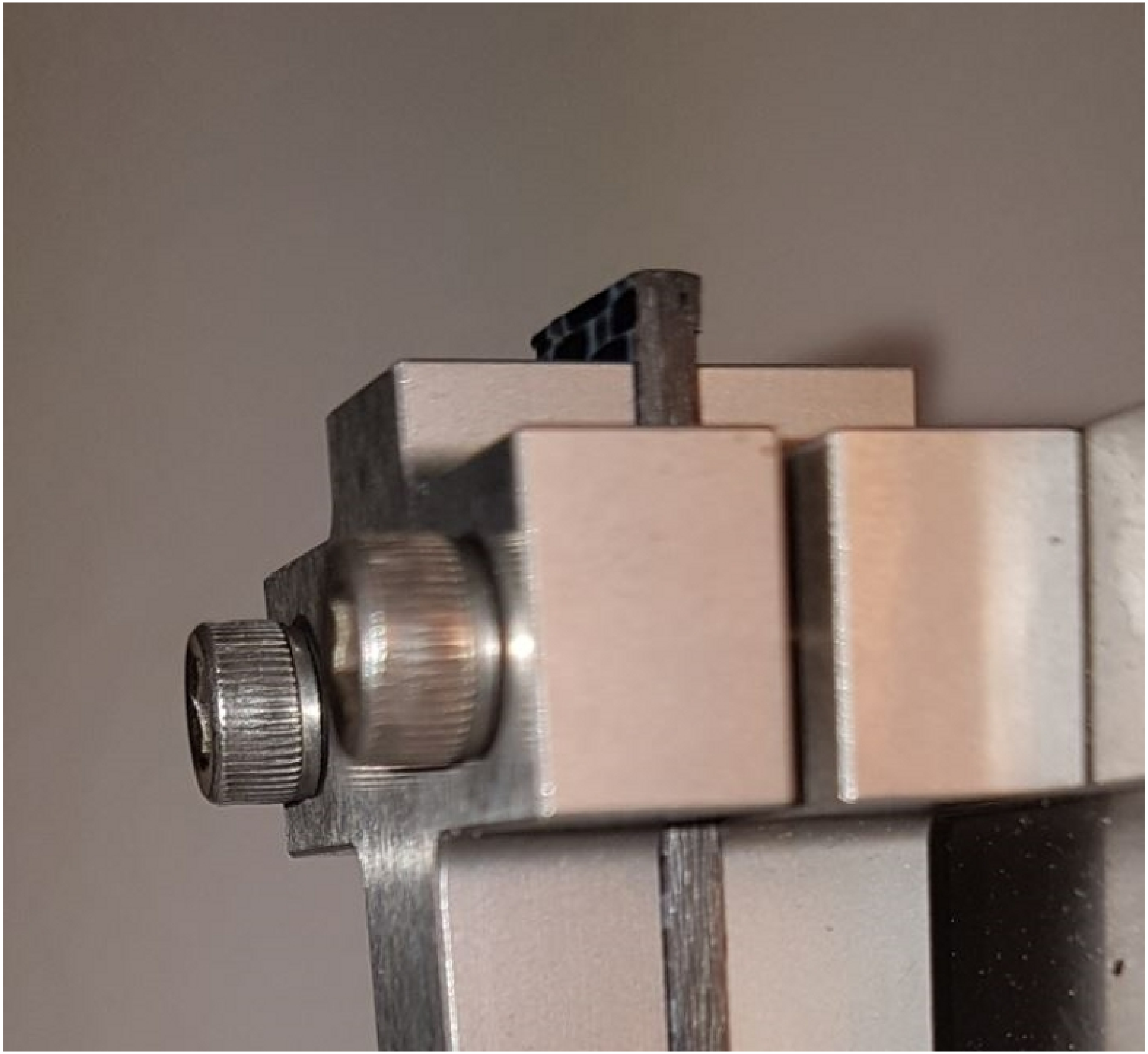

M1-_P1
LAT + LAB
M1-_P2
LIT + LAB
M1-_P3
LAT + LAB + LGM
M1-_P4
LAT + LIB
M1-_P5
LGM

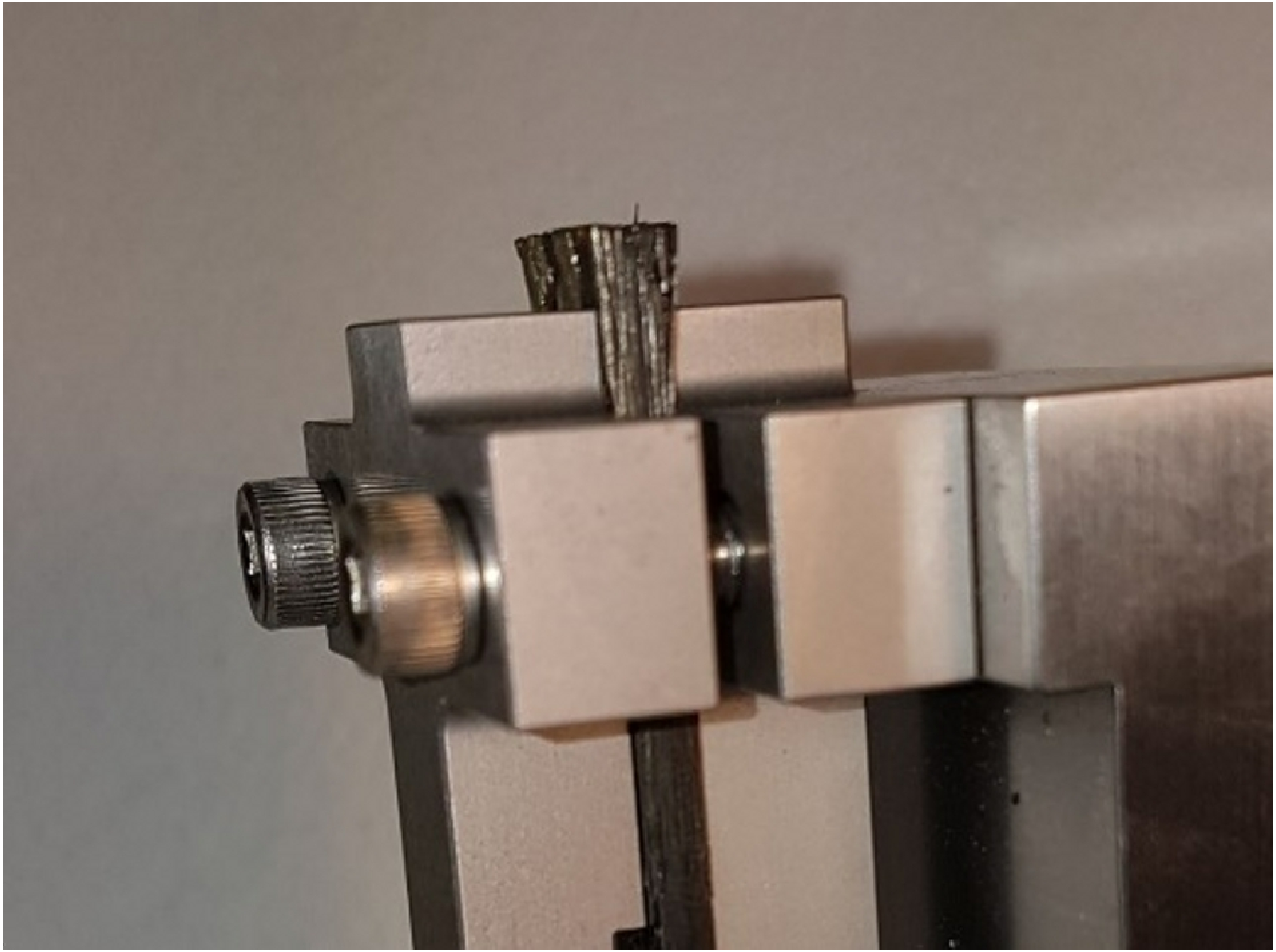

-6000
-5000
-4000
-3000
-2000
-1000
0
0
-50
-100
-150
-200
-250
-300
-350
-400
Stress [MPa]
Strain [10-6 m/m]
Material 1 - 0°
Material 2 - 0°

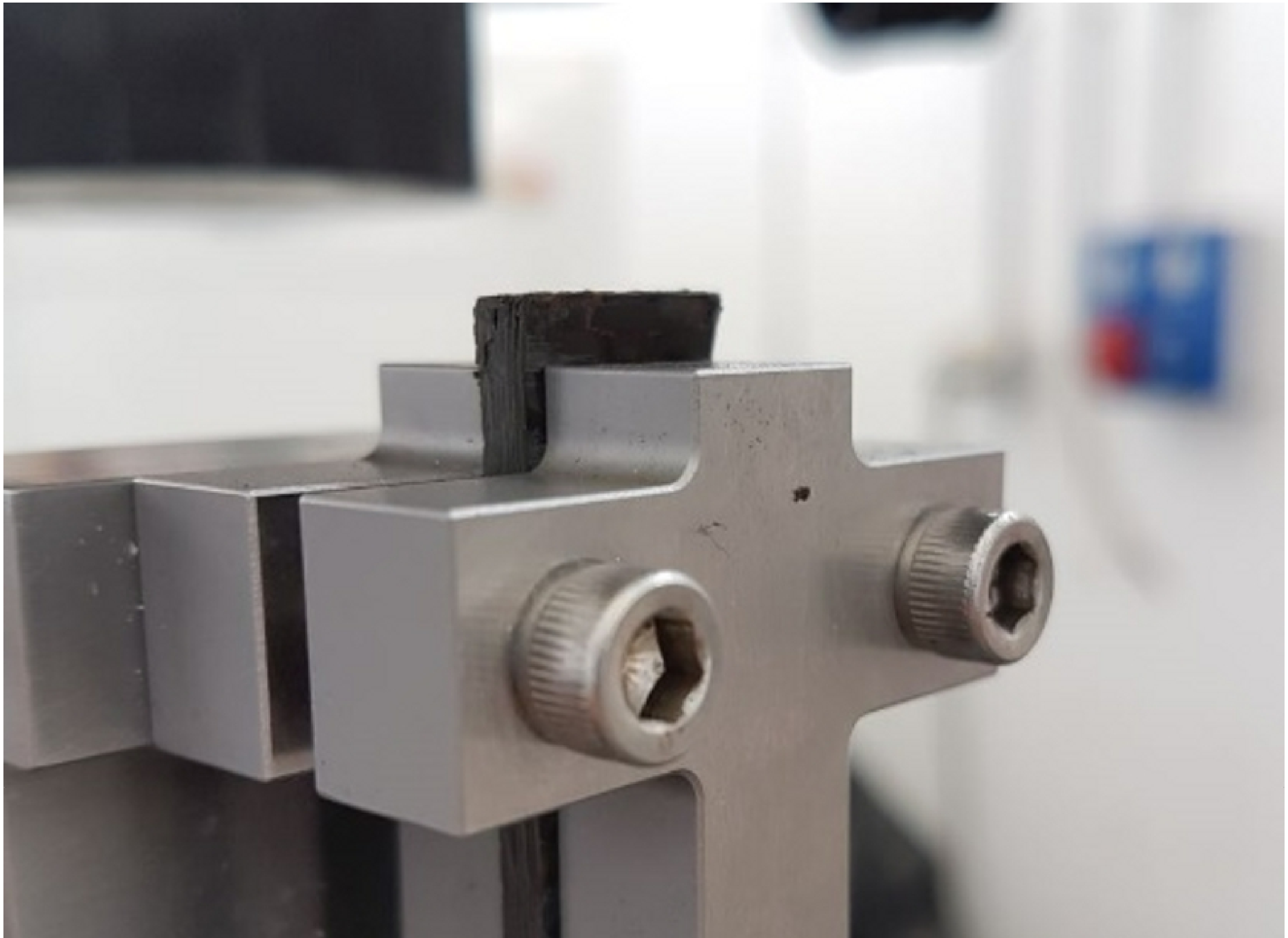

-6000
-5000
-4000
-3000
-2000
-1000
0
0
-50
-100
-150
-200
-250
-300
-350
-400
Stress [MPa]
Strain [10-6 m/m]
Material 1 - 90°
Material 2 - 90°

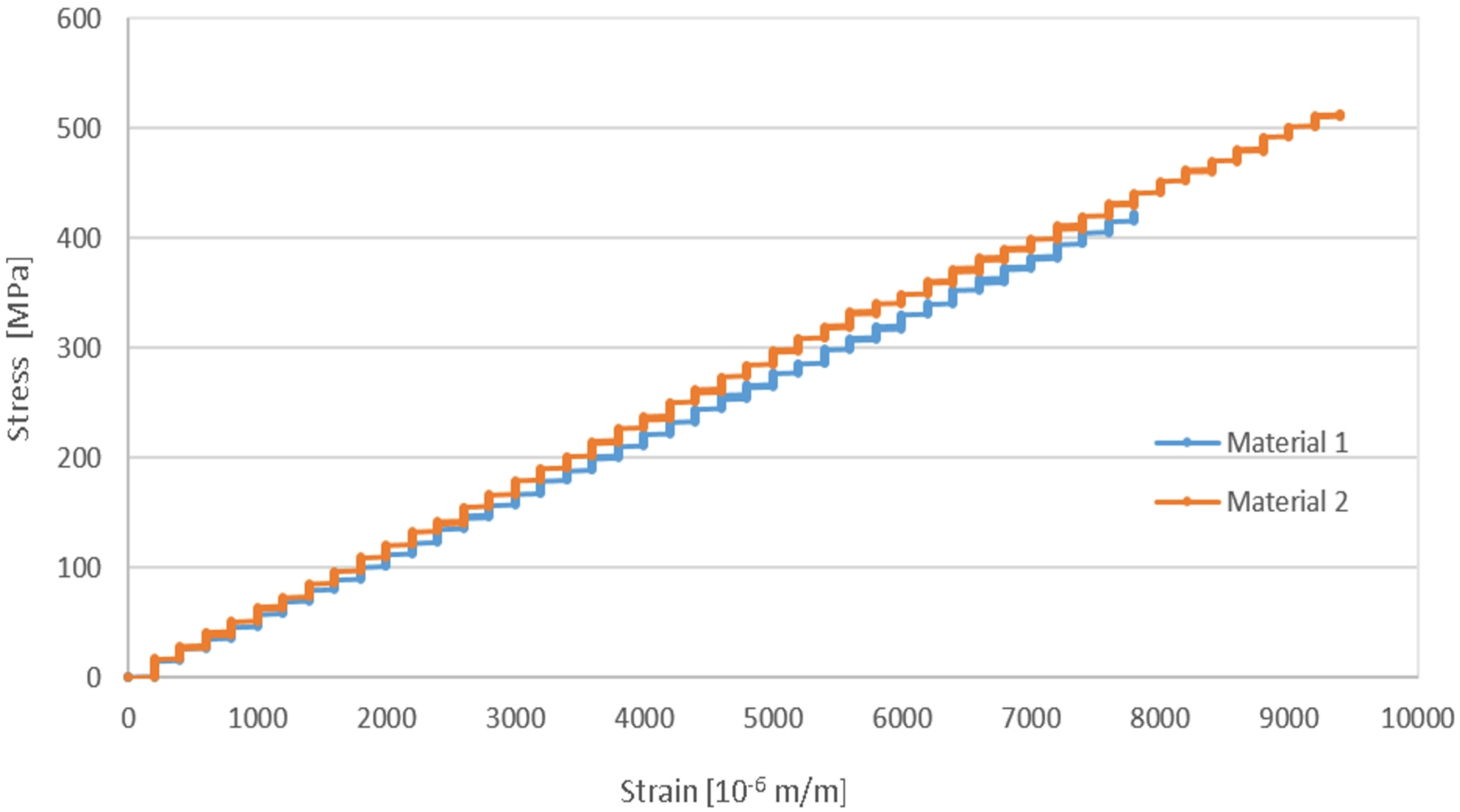

Modulus 0°
Modulus 90°
Compressive Modulus [MPa]
80000
70000
60000
50000
40000
30000
20000
10000
0
Material 1
Material 2
--

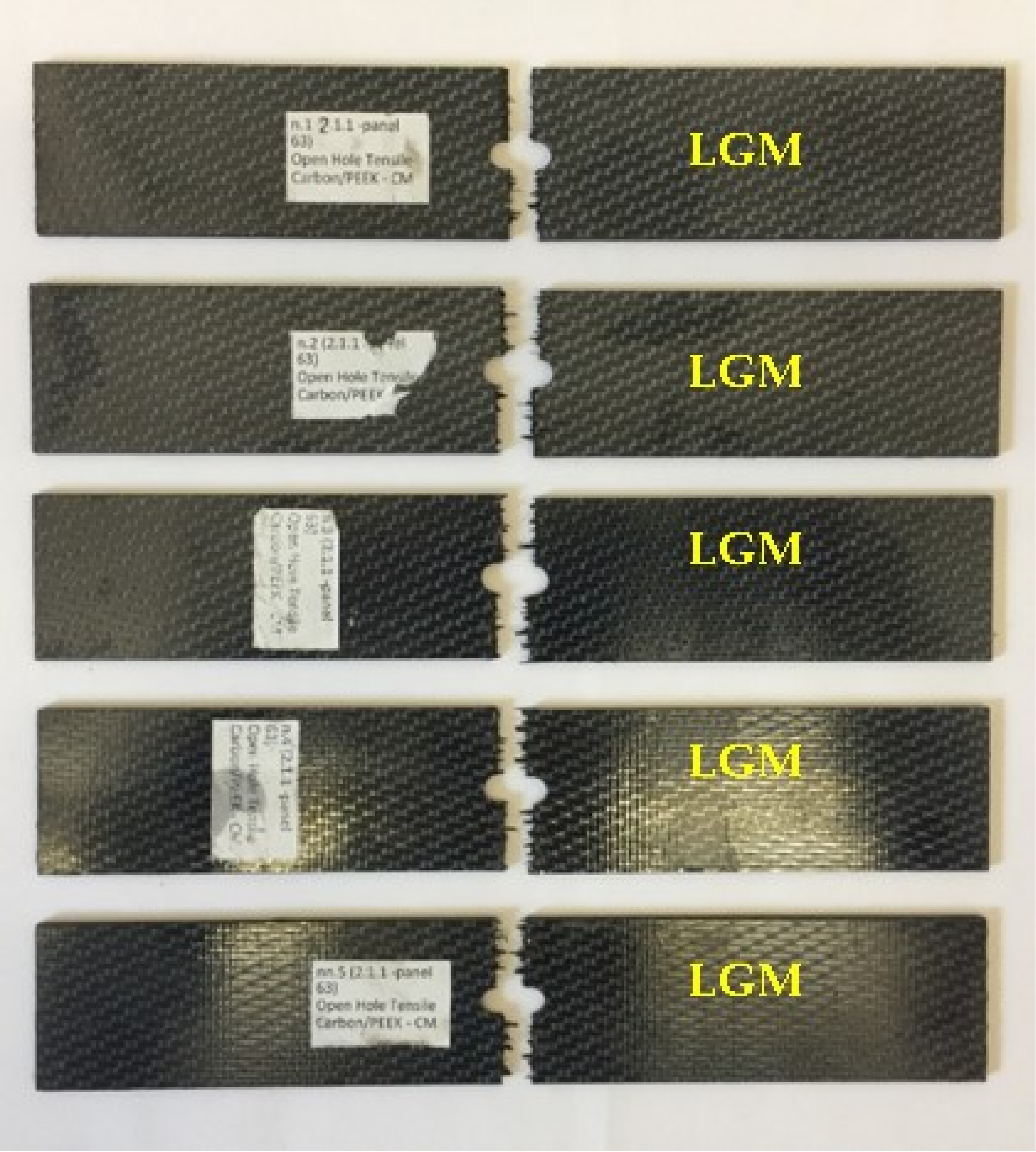









600
500
400
300
200
100
0
Stress [MPa]
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Strain [10^{-6} m/m]
Material 1
Material 2


n.1 2 1.1 -panel 63) Open Hole Tensile Carbon/PEEK - CM
LGM
n.2 (2.1.1 panel 63) Open Hole Tensile Carbon/PEEK
LGM
n.3 (2.1.1 -panel 63) Open Hole Tensile Carbon/PEEK - CM
LGM
n.4 (2.1.1 -panel 63) Open Hole Tensile Carbon/PEEK - CM
LGM
nn.5 (2.1.1 -panel 63) Open Hole Tensile Carbon/PEEK - CM
LGM


Open Hole Tensile
Carbon/
Benzoxazine - RTM
LGM + MGM
Open Hole Tensile
Carbon/
Benzoxazine - RTM
LGM + MGM
LGM + MGM
Open Hole Tensile
Carbon/
Benzoxazine - RTM
LGM + MGM
LGM + MGM