

Comparative Behavior under Tensile and Three-Point Bending Tests for a Composite with Quadriaxial Fabrics and Epoxy Resin

Mario CONSTANDACHE¹, Ioana Gabriela CHIRACU¹, George PELIN²,
George Cătălin CRISTEA^{*,2}, Alexandru Viorel VASILIU¹, George Ghiocel OJOC³,
Lorena DELEANU^{*,1}

*Corresponding authors

¹Center of Excellence in Polymer Processing (CE-PP), “Dunarea de Jos University”,
111 Domnească, Galati, Romania,
mario.constandache@gmail.com, ioana.chiracu@ugal.ro, alexandru.vasilu@ugal.ro,
lorena.deleanu@ugal.ro*

²INCAS – National Institute for Aerospace Research “Elie Carafoli”,
220 Iuliu Maniu, Bucharest 061126, Romania,
cristea.george@incas.ro*, pelin.george@incas.ro

³Autonomous Flight Technologies,
1 Aeroportului, Clinceni, Romania,
george.ojoc@gmail.com

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Abstract: This paper continues recent research of the authors, comparing the experimental results for two test types (tensile and three-point bending), obtained for the same composite. The composite was obtained from 8 layers of quadriaxial glass fiber fabric (with 1200 g/m² and (supplied by Castro Composites Spain) and a bicomponent epoxy resin SikaBiresin® CR82 (supplied by Sika Group Austria). Specimens measured 9 mm × 29 mm × 280 mm, with a bending span of 100 mm and a tensile gauge length of 150 mm. Tests were conducted at rates of 10 mm/min, 200 mm/min, 500 mm/min, and 1000 mm/min. Tests were carried out on Instron 2736-004 universal testing machine. Results show that flexural strength exceeded tensile strength by ~20–26% across all test rates, consistent with the Weibull effect. However, the absorbed energy in tension was more than six times higher than in bending, particularly at higher test rates. Stress–strain curves revealed three characteristic zones: (i) linear elastic, (ii) nonlinear up to maximum stress, and (iii) post-peak failure. Overall, the results demonstrate that mechanical characterization of composites requires both tensile and bending tests. Using only one test type may lead to incomplete or misleading evaluations of structural behavior. For engineering applications, the choice of test should reflect the dominant loading scenario in service. The study confirms that tensile tests capture the composite’s capacity for deformation and energy absorption, while bending highlights outer-layer fragility. Both test types are therefore required for reliable structural characterization and design.

Key Words: quadriaxial glass fiber fabric, glass fiber reinforced polymer (GFRP), tensile test, three-point bending, mechanical characteristics, stress, strain, energy at break, Young’s modulus, test rate sensitivity

1. INTRODUCTION

Composites are increasingly used in design solutions and products [1], [2] due to their rapid processing and due to the possibility of tailoring their properties by changing components and architecture of the composite.

Any new material on the market has to fulfill tests for complying with quality and safety requirements. The number of tests depend on composite applications and the expertise of designers and manufacturers. Also, the beneficiary of the product could ask for specific tests to comply with its intend of use. This is why, today, a datasheet of a composite could contain many characteristics (physical, chemical, mechanical, thermal, test for durability and recycling etc.). After a recent documentation, the authors noticed that many reports and scientific papers focus on only one type of test, especially for traction when presenting a new composite.

Table 1 gives information on traction for polymeric composites with glass fibers (GFRP), for different strain rates, even more than 1000 mm/min. There are presented details of the composite, resin, the sample dimensions, the test rates and experimental results for mechanical characteristics (not all in one referenced paper): tensile stress at break, Young modulus, energy at break and strain at break. Where the specimen dimensions are not specified, standard dimensions according to ASTM D3039 [3] or ISO 527-5 [4] are usually used. Test rates varied depending on the study to assess strain-rate sensitivity. Higher strain rates generally resulted in increased tensile strength and elastic modulus. Not all studies reported the energy at break. Where available, it is included. As for strain at break, values indicate ductility; higher percentages suggest a more ductile behavior. These reports show that tensile stress at break and the Young modulus of GFRP increase with the increasing of test rate and the strain at break decreases, indicating a more brittle behavior under faster loadings.

Table 2 presents information for bending and traction tests on composites, in order to point out that the subject of this paper has been of interest for decades and the results are depending on composite architecture and test loading.

Table 1. Data for tensile tests at higher test rate for GFRP

Reference	The composite	The resin	Sample dimensions	Test rate	Stress at break (MPa)	Young Modulus (GPa)	Energy at break (J)	Strain at break (%)
[5]	Unidirectional GFRP	Epoxy	ASTM D3039 standard	25–200 s ⁻¹	700–900	40–50	Not reported	1.5–2.0
[6]	Thermoplastic s with long glass fibers	Therm o-plastic	Not specified	0.001–400 s ⁻¹	75.4–146.7	5.2–7.3	Not reported	2.8–4.6
[7]	Quadriaxial glass fiber fabric	Epoxy	8 and 16 layers	10–1000 mm/min	300–500 (bend)	20–30 (bend)	Not reported	1.0–1.5
[8]	Chopped strand mat (CSM) GFRP	Poly-ester	Not specified	Not specified	200–250	10–15	Not reported	1.5–2.0
[9]	Unidirectional GFRP	Epoxy	ASTM D3039 [10]	6×10 ⁻⁵ to 260 s ⁻¹	500–800	35–45	Not reported	1.8–2.5
[11]	GFRP with MWCNTs	Epoxy	Not specified	1 mm/min	UTS increases with 15.1% adding 1% MWCNT		Not reported	Not specified

Table 2. Traction versus 3-point bending (and 4-point bending) – fiber reinforced composites

Reference	Material / samples	Standards	Resistance ratio: σ_f/σ_t	Moduli (E_f/E_t)	Energy at break, discussions
[12]	UD graphite/epoxy	ASTM D3039 (traction), ASTM D790 (bend)	> 1 (because of stress gradient in bending and loaded efficient volume)	Not given	„Any attempt to predict tensile-coupon data from flexural data for design purposes is premature”
[13]	GFRP (epoxy)	tensile, 3-point and 4-point bend), Weibull analysis	> 1 ; the ratio depends on efficient volume of high stress; a method for predicting the difference between tests	Not given	flexure tests yield higher strengths than tensile tests
[14]	GFRP bars (semicircle cross section),	ASTM D4476 (bend), CSA S807-10 (Canadian standard)	3-p vs 4-p bending: difference of 2–10%;	Not given	”3-point and 4-point bending tests provide similar results, the difference between results being 2% to 10%, suggesting both tests can be used for tensile strength determination of GFRP bars”; energy is not numerically reported
[15]	GFRP plate with different matrixes	ISO 527 (traction), (bending: original method)	The ratio depends on the resin;	E_t^* and E_f^{**}	Not given
[16]	GFRP laminates (with different fibers, not only glass	SR EN ISO 527-1 [23], ISO 527-4	— (only traction)	E_t : 22–31 GPa	Not given
[17]	GFRP laminates – 4-point bending and traction (two fiber directions)	ASTM D790, ASTM D3039	Curves and values for stress -strain but not a general discussion on them	E_f (tangent); E_t as in D3039	Curves force – displacement; values for „work to max load” is not given

* E_t – tensile modulus, ** E_f – flexural modulus

This paper presents the experimental results for the same composite, but for two type of tests: traction and three-point bending, in order to help engineers in designing and modeling the behavior of a composite structure.

2. MATERIALS, TEST METHOS AND EQUIPMENT

The composite has a reinforcement fabric made of four sublayers oriented at 0° , $+45^\circ$, 90° , and -45° , respectively, suggesting a quasi-isotropic in-plane behaviour. The commercial product is designated as Quadriaxial Glass Cloth 1200 g/m² ($0^\circ/+45^\circ/90^\circ/-45^\circ$), code WTVQX1200-1 E-glass, Q1200E10Q (supplied by Castro Composites [18]). Each of the four sublayers has its own areal density, 283 g/m², 300 g/m², 307 g/m², and 300 g/m², respectively, with stitching as additional areal density of 10 g/m², the total areal mass being approximately 1200 g/m² ($\pm 3\%$).

The matrix is a bicomponent resin SikaBiresin® CR82 with the hardener CH80-2 [19]. The fabrication of the composite is detailed in [7], [20].

The following equipment was used in the tensile tests: the Instron 2736-004 universal testing machine [21] and the Instron AVE extensometer [22], both from the Advanced Materials and Tribology Laboratory – INCAS. The tests were performed on the Instron 2736-004 universal testing machine (INCAS Bucharest), which can perform tensile, compression, and bending tests, with a nominal loading of 100 kN, with a thermally controlled chamber for a temperature range of -73 °C to +315 °C.

Figure 1 presents the stress – strain curves for the tensile tests carried out at 500 mm/min, as obtained with the dedicated soft of the test machine Instron 2736-004. One may notice that the yellow curve is deviated from the results bunch, so, this test was eliminated from the experimental results.

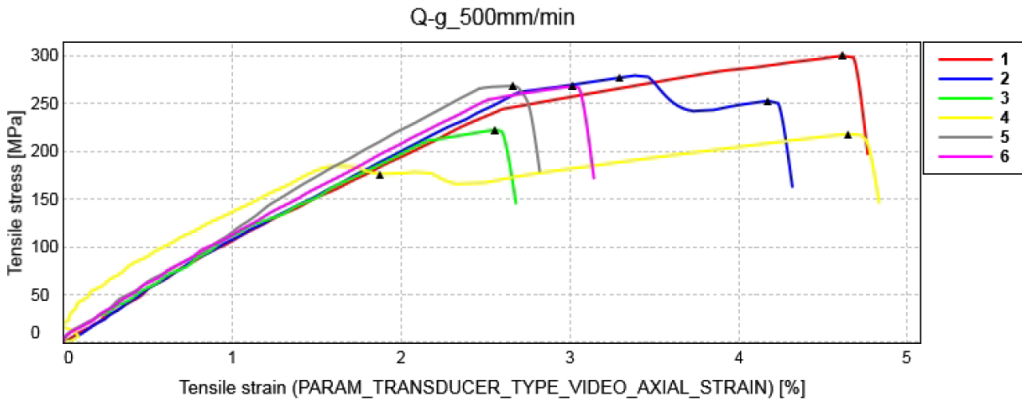


Figure 1. Stress – strain curves for the composite (6 teste), at test rate 500 mm/min

The parameters obtained from 5 representative tests (maximum force, Young's modulus, tensile strength, elongation at break, energy at break (at maximum force), for each test rate are given as average values, together with the standard deviation.

In principle, 5 tests are performed at the same test rate. If one or more of the curves differ significantly, several additional tests are performed and the extreme tests are discarded.

The new standard SR EN ISO 527-1 [23] does not have definitions for the yield point and proportional limit because the idea of trying to specify the extension of the linear portion of the stress-strain curve has been abandoned. The tensile test is normally performed at one of the standard rates, chosen from a set of values given in the standard or in the technical manual of the testing machine [24], [25], [26].

For traction tests, the results were expressed by the help of the following relationships:
The actual stress (simply named tensile stress here)

$$\sigma = F/A \quad (1)$$

The engineering stress (simply named here as tensile stress)

$$\sigma_{eng} = F/A_0 \quad (2)$$

The strain (also engineering)

$$\varepsilon_{eng} = \Delta L/L_0 \quad (3)$$

where F is the applied force, at moment t , A – the cross section of the sample at moment t , A_0 – the initial cross section of the sample, L_0 – the sample length between marks (the length where the load is applied).

For the three-point bending, ISO 14125 [28] proposes the main formula for rectangular cross section

$$\sigma_{f,max} = \frac{3F_{max}L}{2bh^2} \quad (4)$$

$$\varepsilon_{f,max} = \frac{6sh}{L^2} \quad (5)$$

$$E_f = \frac{L^3m}{4bh^3} \quad (6)$$

where F_{max} is the maximum force at midpoint, L – the support span (here 100 mm), b – the sample width, h – the sample thickness, s – the mid-span deflection (displacement) and m – the slope of the initial linear part of the force – displacement curve.

3. THE INFLUENCE OF TEST RATE ON MECHANICAL CHARACTERISTICS

Why did we select four test rates for both loadings, traction and bending? The first value (10 mm/min) is often used to assess composite quality, but it is very rare in practice. The other three values (200 mm/min, 500 mm/min and 1000 mm/min) are bigger and could occur in practice. We selected these four values after a documentation, including standards [10], [29], [30], [38] [45], books [17], [21], [23], [25], [31]-[34] and scientific papers [35]-[37], [41], [44].

Mallick P.K. [39] in "Fiber-Reinforced Composites: Materials, Manufacturing, and Design" presents in detail the tensile properties of composites and the testing methods. Daniel I.M. and Ishai O. [40], in "Engineering Mechanics of Composite Materials" offer a perspective on the mechanical behavior in traction and a link between test practice and theory. Chamis, C.C. [41], in "Simplified Composite Micromechanics Equations for Strength, Fracture Toughness and Environmental Effects" discussed the mechanical behavior of composites, including those obtained by traction tests. Bledzki A.K. and Gassan J. [42], in the paper „Composites Reinforced with Cellulose Based Fibres“, even if they concentrated on natural fibers, this review included data about tensile tests of the composites based on polymeric matrix and glass fiber reinforcement (GFRP).

For tensile testing of glass fiber reinforced polymer (GFRP) composites, the test rate—in particular, the crosshead speed or strain rate - is a critical parameter that influences the accuracy and comparability of results.

ASTM D3039 [10] is the widely recognized standard for determining the tensile properties of polymer matrix composites, including GFRPs. It specifies two main methods for establishing the test rate:

- constant strain rate: a nominal strain rate of 0.01 min^{-1} is usually applied,
- constant crosshead speed: a nominal speed of 2 mm/min is one of the lowest value in tensile tests. But many engineers and researchers used different values. For instance, Wang F. et al. [43] used 20 mm/min. These lower rates are designed to ensure consistent and comparable results across different laboratories and test scenarios.

When performing tensile tests on GFRP composites, ensure that specimens are prepared according to standard dimensions and instructions to avoid introducing variability, maintain constant environmental conditions (e.g., temperature, humidity) during testing, as these factors can influence the results, and use appropriate sensors and data acquisition systems to accurately capture stress-strain behavior, especially at higher strain rates.

Standard tensile test rates, such as those specified by ASTM D3039 [10] (2 mm/min), may not capture the strain rate-dependent behavior of glass fiber reinforced polymer (GFRP) composites at higher loading rates. Recent studies have explored the effects of high test speeds, including 1000 mm/min, on the mechanical properties of GFRP materials. Research indicates that GFRP composites exhibit increased tensile strength and stiffness at higher strain rates. For example, a study investigated the tensile behavior of 8HS 7781 glass fiber composites at strain rates up to 1000 s^{-1} , observing a notable increase in peak stress and a slight decrease in stress to failure at higher rates [43].

When performing tensile tests at high loading rates, such as 1000 mm/min, it is essential to consider the following: ensure that the testing equipment can accurately capture rapid changes in load and displacement to obtain reliable stress and strain data, maintain consistent sample dimensions and alignment to reduce variability in results; high strain rates can alter failure modes, so post-test examination of fracture surfaces can provide insight into material behavior under dynamic loading. By considering these factors, you can effectively evaluate the tensile properties of GFRP composites at high strain rates, providing valuable data for applications involving dynamic or impact loading conditions [44].

SR EN ISO 527-5 [4], [45] focuses on unidirectional fiber-reinforced plastic composites and does not prescribe a fixed test speed. Instead, it emphasizes the importance of selecting a test speed that ensures accurate measurement of tensile properties, particularly in the elastic region of the material. In practice, test speeds can vary significantly depending on the specific objectives of the test and the characteristics of the material. For example, while standard test speeds such as 2 mm/min are commonly used for material characterization, higher speeds such as 1000 mm/min may be used for quality control or to simulate dynamic loading conditions. This speed does not compromise the accuracy of the measured properties, particularly the tensile modulus. This can be achieved by comparing the results obtained at different speeds or by consulting the relevant literature that explores the strain rate sensitivity of similar materials.

Tensile test rates for glass fiber reinforced polymer (GFRP) composites vary widely in the literature, depending on the objectives of the study, materials, and testing standards.

Ou et al. [5] report a mechanical characterization of the tensile properties of glass fiber and its reinforced polymer composite (GFRP) at different strain rates and temperatures. This research focused on unidirectional GFRP composites tested at strain rates of 25 s^{-1} , 50 s^{-1} , 100 s^{-1} and 200 s^{-1} at temperatures ranging from $-25 \text{ }^{\circ}\text{C}$ to $100 \text{ }^{\circ}\text{C}$. The study found that tensile strength increased with strain rate, while strain at break decreased, highlighting the sensitivity of GFRP materials to strain rate.

These studies demonstrate the diversity of tensile test rates applied to GFRP composites, ranging from quasi-static rates to high strain rates, depending on the field of research interest. When selecting a test rate, it is essential to consider the specific application and standard or experimental conditions relevant to your study.

Certain universal testing machines (UTMs), such as those from Instron or ZwickRoell [45], [46], can achieve crosshead speeds of up to 2000 mm/min or even 5000 mm/min. the Instron 5942 tensile testing machine offers a speed range between 0.05 mm/min and 2500 mm/min [24], making it suitable for high-speed tensile testing applications. However, tensile tests on glass fiber reinforced polymer (GFRP) composites at these high speeds are relatively

rare in the literature. This lack is often due to equipment limitations and challenges associated with high-speed testing. Most studies focus on strain rates up to approximately 400 s^{-1} , which correspond to lower crosshead speeds, depending on the length of the specimen. A study by Zhang et al. [9] investigated unidirectional GFRP specimens at strain rates up to 317 s^{-1} , observing significant increases in tensile strength and modulus of elasticity with increasing strain rate. However, as discussed earlier, tensile tests on glass fiber reinforced polymer (GFRP) composites at these high speeds are relatively rare in the literature. This rarity is often due to equipment limitations and challenges associated with high-speed testing.

Figure 2 shows the stress-strain graphs as obtained using the dedicated software of the Instron 2736-004 tensile testing machine [24], for several test sets.

The average values obtained from 5 representative tests for the parameters maximum force, Young's modulus, tensile strength, elongation at break, and energy at break (at maximum force) for each test speed are given in Figures 9-10, including the standard deviation.

If one or more of the first 5 curves obtained differ significantly in shape and/or extreme values (as yellow curve in Fig. 2), several additional tests are performed so that 5 representative curves remain.

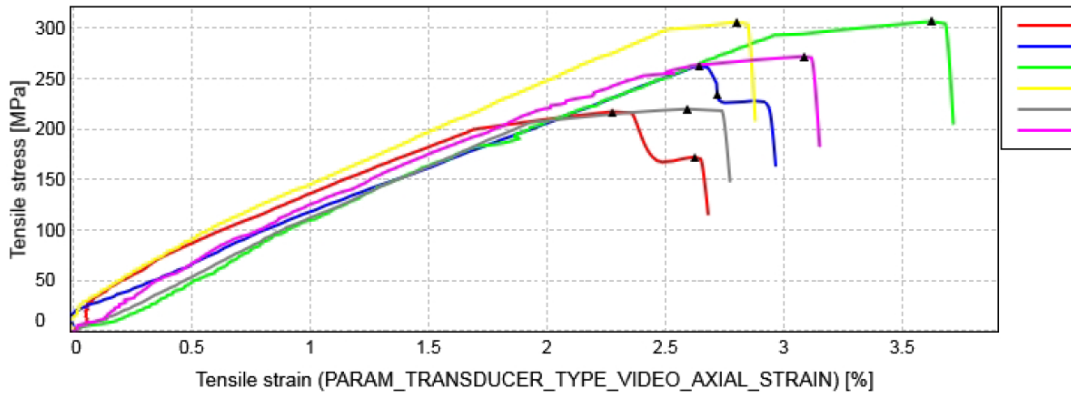


Figure 2. Stress – strain curves, as given by the dedicated software of the test machine (extreme behavior were eliminated; here, test 4 was not taken into account, at 200 mm/min)

The ASTM D3039 [10] standard is widely applied for determining the tensile properties of polymer matrix composites reinforced with continuous fibers, including glass fibers. The testing speed is specified according to the type of material and the purpose of the test. For instance, for rigid materials, a recommended speed is 2 mm/min , whereas for more flexible materials it may be 5 mm/min . It is essential to consult the standard in order to establish the appropriate speed for a given application.

SR EN ISO 527-4 [38] and SR EN ISO 527-5 [4]. These European standards address the tensile testing of fiber-reinforced composites. The testing speed is defined by the specimen type and the test objective. For material characterization, lower speeds are recommended, while for quality control purposes, higher speeds may be applied.

In dedicated literature, the strain rate may be also expressed as:

$$\dot{\epsilon} = \frac{v}{L_0} [\text{s}^{-1}] \quad (7)$$

And calculating after relationship (7), the values in table 3 are obtained.

Tabelul 3. Values of test rate and strain rate for tensile tests

Test rate		L ₀ [mm]	$\dot{\epsilon} = \frac{v}{L_0}$ [s ⁻¹]
[mm/min]	[m/s]		
10	0.000166	150	1.10×10 ⁻³
250	0.00416		27.73×10 ⁻³
500	0.00833		55.53×10 ⁻³

Table 4. Test campaign

Material	Traction		Three-point bending	
	Test rate [mm/min]	Tests	test rate [mm/min]	Tests
Q-g	10	XXXXXX	10	XXXXXX
	200	XXXXXX	200	XXXXXX
	500	XXXXXX	500	XXXXXX
	1000	XXXXXX	1000	XXXXXX

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

Figure 3 presents lateral and back views of the tested samples in bending for a) 10 mm/min and b) for 1000 mm/min. At 10 mm/min, lateral views show that the failures are concentrated at the bottom part of the composite (the front being the surface where the bending indenter acts), but also cracks are visible on the first layers. The front view of the bottom sides of the samples reveals the influence of the yarns’architecture. As the yarns are oriented at 45° on the last layer, one may notice that these short yarns are debonded or delaminated, but they are not broken in cross section. At 1000 mm/min (Fig. 3), the failures are more visible in the lateral side. More layers are debonded/delaminated, but not all the layers are broken, meaning that this type of composite fails in steps (as it will be seen on curves as saw teeth). The view of the composite bottom does not differ too much from those of the samples tested at 10 mm/min.

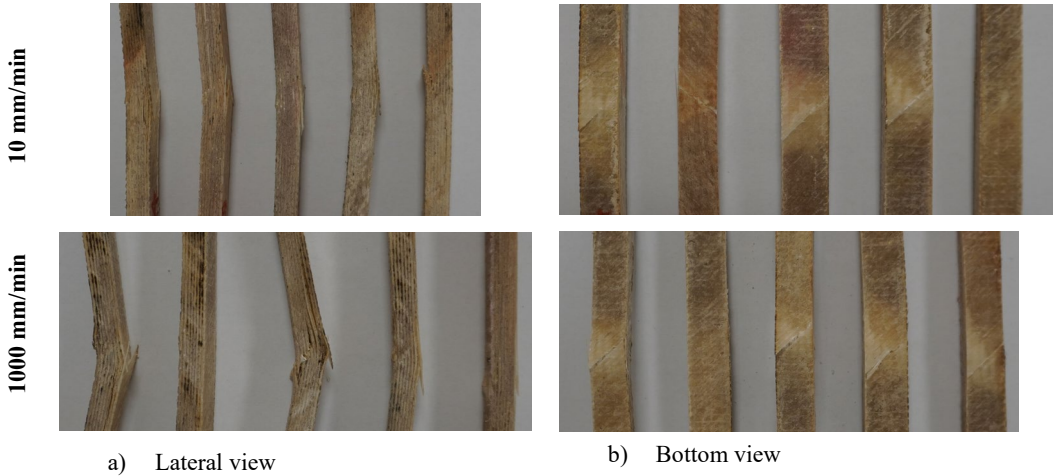


Figure 3. Samples tested in 3-point bending

In traction, sample failures are more spectacular and the test rate influences much more the sample aspect after tests (Fig. 4). Analysing the force evolution for both loadings (Fig. 5), one may notice a very huge difference between maximum values between bending (right columns) and traction (left columns). At 10 mm/min (a), failure is localized, with cleaner

breaks and limited fiber pull-out. At 1000 mm/min (b), failures are more extensive and irregular, with multiple fracture planes, delamination, and significant fiber pull-out, indicating stronger influence of loading rate on fracture mechanisms.



Figure 4. Samples tested in traction

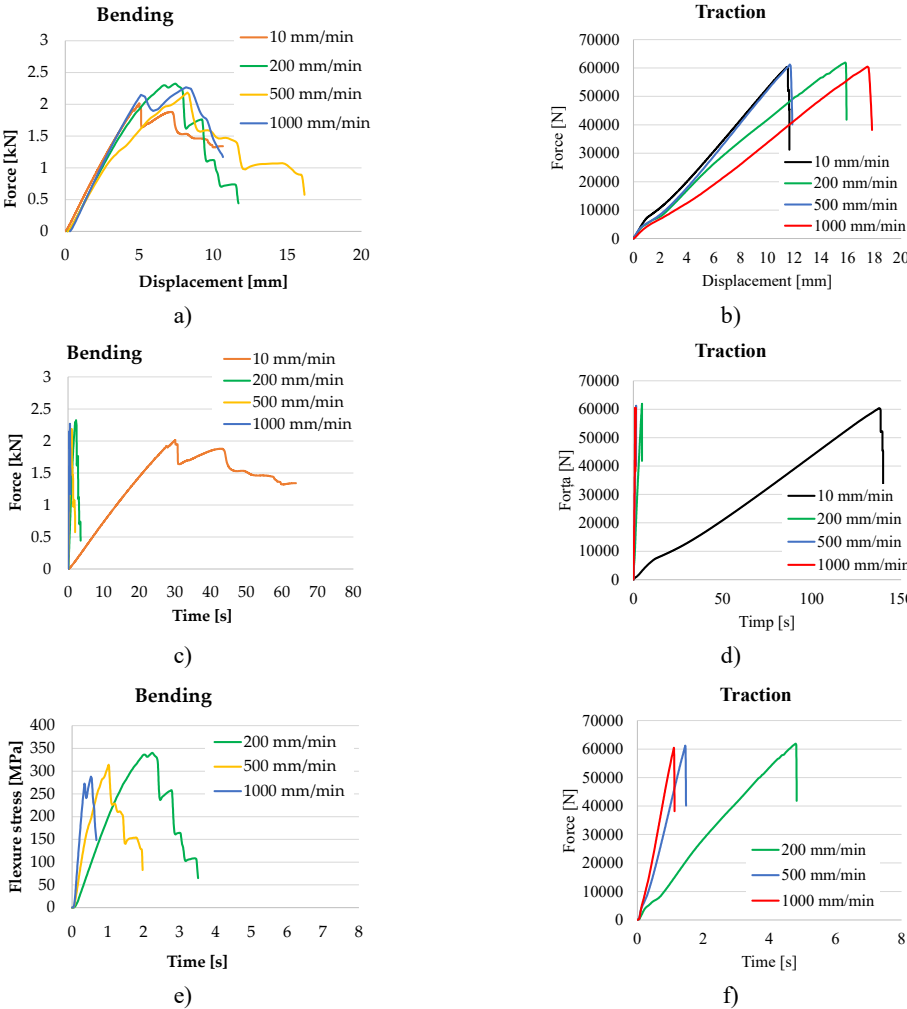


Figure 5. – Force – displacement curves for all test rates: a) bending, b) traction, force – time curves: c) bending, d) traction; force – time curves for higher test rates: e) bending, f) traction

Maximum force is occurring between a displacement of 5 mm to 8 mm for bending, but in traction, the maximum force is generated between 11 mm and 17 mm (Fig. 5a and b). In bending the slope of these curves is less differentiated in the linear zone, but in traction the slope depends on the test rate. When analyzing the force evolution in time. One may notice that, at 10 mm/min, the maximum force in bending was at approx.. 30 s, but in traction, this parameter was evident at approx. 130 s. For the higher test rates the time when maximum force appears is evident only for 200 mm/min.

Because, in bending, break is generated on a small volume of material, especially on exterior layer in traction of the composite (the surface opposing the action of the indenter), where the stress exceeds the stress at break. But in traction, all the cross section of the sample is relatively even loaded and the force has to be higher to break the composite. Thus, measuring the force in structures under traction or bending loads are not significant if the engineer does not know the type of loading. Both curves have approximately linear evolution, but for this composite, the slope of these curve seems insensitive to test rate in bending, at least for approx.. 70% of the range till maximum stress occurred. In traction, slope of the same material are different, greater for higher test rates. When analyzing the force evolution in time, for each test, the maximum value of the force seems not to be sensitive to test rate, meaning approx.. 2.3 kN for bending and approx. 61000 N for traction. Figure 5e and Figure 5f are drawn only for higher test rates in order to point out that force gradient is bigger when test rate increases.

Figure 4 presents typical curves for stress – time for all test rates and in Figure c) and d) only the curves for the high test rate are drawn.

The stress – strain curves reveal more about the behavior of the composite (Figure 7).

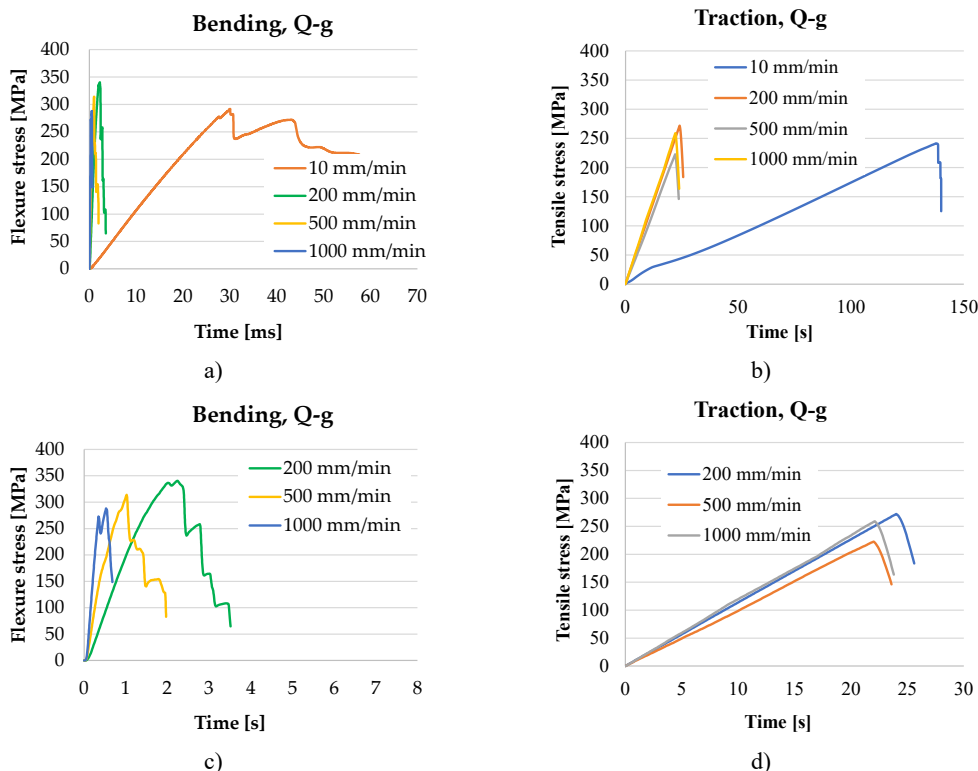


Fig. 6 – Stress – time curves for all test rates: a) bending, b) traction; stress – time curves for higher test rates: c) bending, d) traction

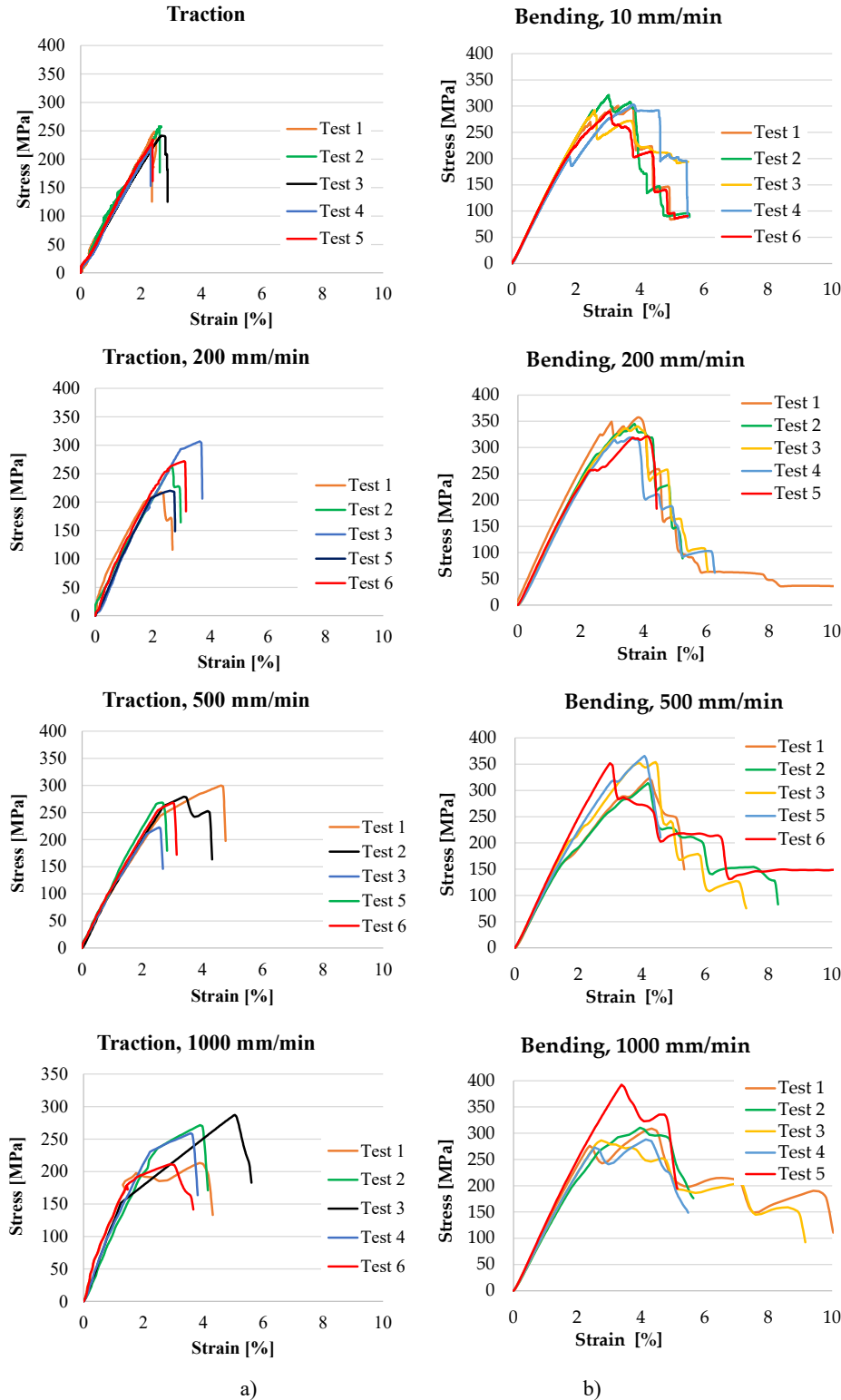


Figure 7. Stress – strain curves for: a) traction and b) bending

Both loadings generates three zones:

- a linear zone, very useful to be known for designers
- a non-linear evolution till maximum value,
- the decreasing till total break of the sample.

Even if the first stage of linear dependency between stress and strain characterize both loadings, the maximum values are higher for flexural stress and lower for tensile stress. The maximum flexural stress is ranging from 2% to 4%, and in traction, this band is quite similar, meaning the failure mechanisms could be the same – fiber breakage. In traction, the sample is broken in a shorter period of time with sharp decrease of the measured force, but in bending the decrease of force is visibly in steps, suggesting a successive break of the composite layer.

In bending (Figure 5a) the values of maximum stress do not depend on test rate. The linear zone of the curves is clear straight till 160 MPa and to 260 MPa, except for the test at 500 mm/min. The slope is hard to be differentiated at least till 160 MPa. Thus, in bending the linear behavior (elastic, too) is not depending on test rate. In traction, the linear zones have different slopes, with a slight tendency of depending on test rate. The second zone of the curves is saw teeth-like in bending but the second zone in traction has a variable length zone (it seems to be longer if the test rate is higher). The third zone is also teeth-like and the final strain differs a lot. In traction, the third zone is a sharply descendent line and the strain could be larger when test rate increases (except the test at 500 mm/min)

In literature [12-17], σ_f (3-point or 4-point bending) is usually greater as σ_t for the same composite, due to Weibull effect, related to efficient volume and to the stress gradient in cross section for bending [12]. This concept was validated by Cattell & Kibble [13].

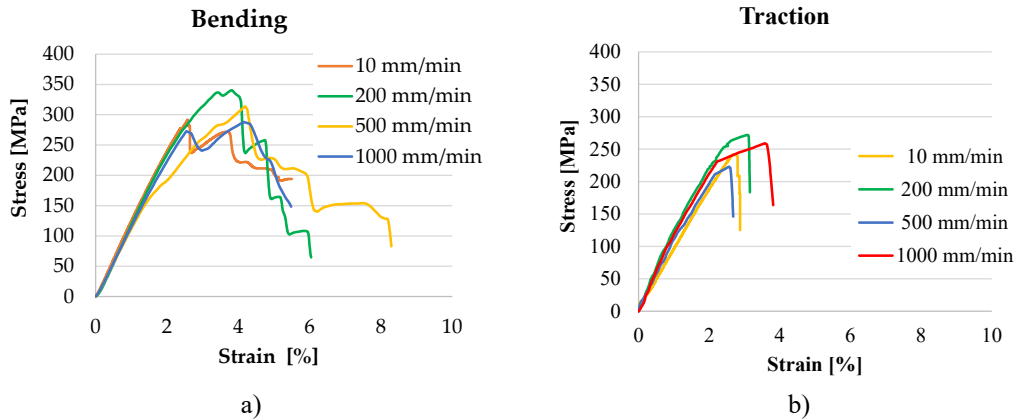


Figure 8. Stress – strain curves for both loadings

Figure 9 shows the characteristics of this composite. The test specimens are relatively uniform in thickness. F_{max} tends to increase with the test speed. The modulus varies between 12.51 GPa and 14.45 GPa, so it does not have a clear dependence on the test rate. The maximum stress increases slightly with the test speed. Unlike homogeneous materials, this composite has increasing deformation with the test speed, at least over the test range. The energy absorbed by deformation and tensile rupture increases with the test rate.

The sample thickness (Fig. 9a) shows that samples have a small variation of this geometrical parameter, maybe except for the tensile tests at 10 mm/min, as the average was 9.11 mm. The value of stress and strain is determined taking into account the actual values for thickness and width for each sample.

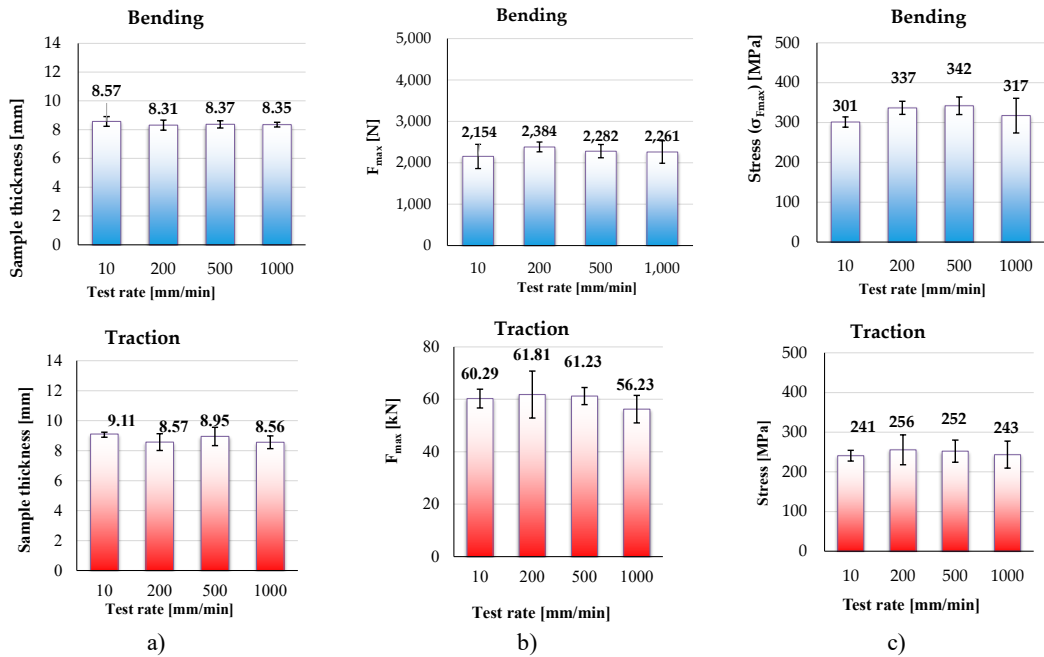


Figure 9. Comparative average values for bending (up) and traction (down): a) thickness, b) F_{max} , c) stress

The big difference is exhibited for F_{max} (Fig. 9b), more than 25 times, as in bending, the fibers on the bottom surface (opposing the face where the bending load acts), are stretched and could break under a smaller load because they are few, but in traction the load has to act on all fibers in the cross section of the sample.

For GFRP bars (not laminates), 3p vs. 4p give similar results ($\pm 2-10\%$); the "scaled" flexural stresses reproduce direct traction well (diff. 0–7%, with one case at 18% on small diameter). This is very useful if you want to estimate σ_t from 3p.

For laminated GFRP, studies with both tests in the same paper are rare in open access; where they appear [17], curves and absolute values are reported; energy up to σ_{max} is not usually a standardized parameter in ISO 14125 [28] (but it is easy to integrate from force – displacement curve, if you have the raw data).

Translated with DeepL.com (free version) For the tests we carried out, the stress at break for bending was bigger as compared to values obtained in traction. Thus,

- for 10 mm/s, the tensile stress was 20% smaller than the bending one,
- for 200 mm/min, the tensile stress was 24% smaller than the bending one,
- for 500 mm/min, the tensile stress was 26.3% smaller than the bending one
- for 1000 mm/min, the tensile stress was 23.3% smaller than the bending one.

For the first test rates (10–500 mm/min) it could be noticed a slight increase both for tensile and bending stress, but the values obtained for 1000 mm/min is not in that trend. Also, the variation are under 10% for each type of loading and a clear dependency of stress to test rate is not obvious.

For strain (Fig. 10a), too, the difference between values for each type of loading is small, but a low increase could be noticed. Young modulus (Figure 10b) is not depending on test rate for bending and it is on a larger spread range for traction. This could be caused by the fact that diagonal yarns do not participate in resisting to traction; they, statistically, are prone to debond/delaminate faster when loading in traction.

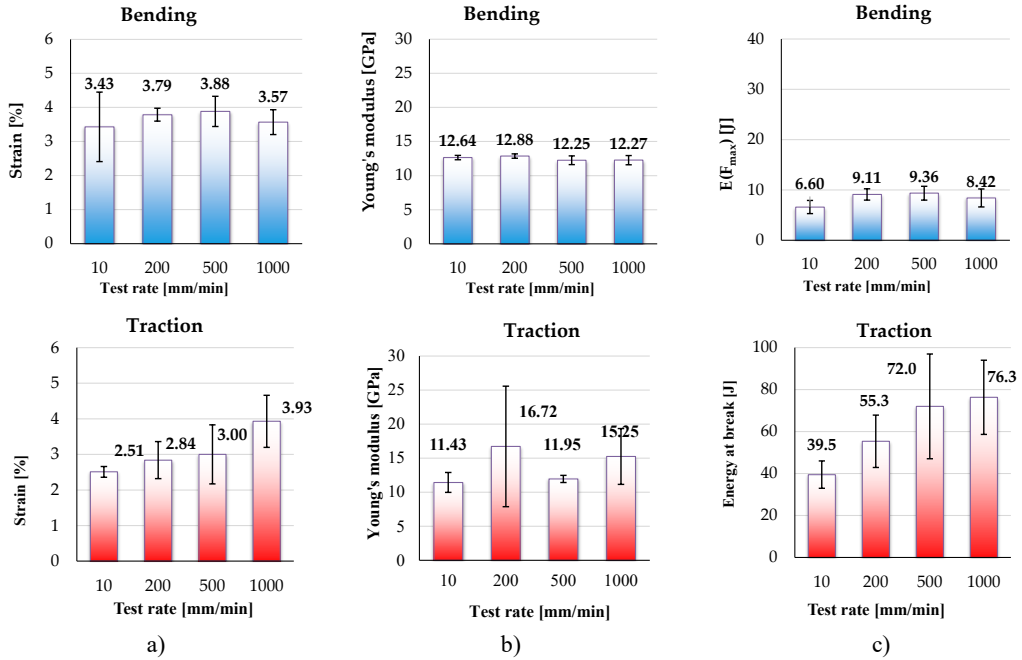


Figure 10. Comparative average values for bending (up) and traction (down): a) thickness, b) F_{max} , c) stress

The absorbed energy is smaller in bending, almost 6 times smaller than values obtained on the same material in traction (Fig. 10c). Difference becomes bigger for higher test rates.

5. CONCLUSIONS

The comparative study between tensile and three-point bending tests on the quadriaxial glass fiber/epoxy composite confirmed that flexural strength values are consistently higher than tensile strength values, with differences ranging from ~20% to ~26% depending on the test rate. This behavior is consistent with the Weibull effect, linked to the smaller effective stressed volume in bending.

The maximum load capacity differs significantly between loading modes: in bending, failure initiates in the outer layers under tension, while in traction the entire cross-section is engaged. Consequently, tensile failure requires substantially higher absolute force, but the normalized stress values highlight the higher flexural resistance.

The test rate showed limited influence on stress values for both loadings. Tensile strength and modulus exhibited slight increases at higher rates, whereas flexural results were comparatively insensitive. The absorbed energy, however, increased more visibly in traction than in bending as the test rate rose.

Stress-strain curves for both loading modes displayed three distinct zones: (i) an initial linear region, relevant for structural design, (ii) a non-linear evolution up to the maximum, and (iii) a descending branch until rupture. Bending showed stepwise post-peak behavior (progressive ply failure), while tensile loading caused abrupt fracture.

The absorbed energy was much higher in traction—more than six times greater than in bending—especially at higher test rates. This suggests that tensile testing better captures the material's capacity to withstand deformation before rupture, while bending emphasizes outer-layer fragility.

Overall, the results demonstrate that mechanical characterization of composites requires both traction and bending tests. Using only one test type may lead to incomplete or misleading evaluations of structural behavior. For engineering applications, the choice of test should reflect the dominant loading scenario in service.

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