

## FLEXURAL BEHAVIOR OF BIAXIAL ( $\pm 45^\circ$ ) NON-CRIMP GLASS FIBER COMPOSITES: INFLUENCE OF TEST RATE AND LAMINATE THICKNESS

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**Abstract:** This study investigates the flexural behavior of biaxial  $\pm 45^\circ$  non-crimp glass-fiber composites manufactured with an unsaturated polyester resin matrix. Three-point bending tests were performed on laminates with different numbers of fabric layers and at several test rates, in order to evaluate the influence of laminate thickness and loading speed. The analysis included not only maximum flexural stress and strain, but also maximum force, time to maximum force, flexural modulus, displacement at maximum force and absorbed energy up to maximum force. The results showed that laminate thickness was the dominant factor controlling the bending response. The maximum force and absorbed energy increased strongly with the number of layers, while the displacement at maximum force decreased as the laminates became thicker. The maximum flexural stress became more dependent on thickness at higher test rates, whereas flexural strain and modulus showed weaker or more scattered trends. The post-peak response was highly irregular, reflecting progressive damage mechanisms typical of layered fabric composites. The obtained results indicate that thicker biaxial glass-fiber composites provide improved load-carrying capacity and energy absorption, which is relevant for lightweight marine structures and severe loading events.

**Keywords:** three-point bending, flexural characteristics, biaxial glass fiber fabric, composite, test rate

### 1. Introduction

Flexural (bending) testing plays a crucial role in the characterization of composite materials, as it provides insight into their behavior under complex loading conditions that closely resemble real service situations [1-5]. Unlike simple tensile or compressive tests, bending induces both tensile and compressive stresses within the same specimen, allowing for a more representative evaluation of strength, stiffness, and failure mechanisms.

Parameters obtained from such tests—such as flexural strength and flexural modulus—are directly used in structural design, together with appropriate safety factors, to ensure reliability and durability. These tests are essential in industries where a high strength-to-weight ratio is critical, including aerospace (wing structures, fuselage components), marine (hulls, structural panels) [6, 8], automotive (body panels, chassis elements) [9], and protective applications (impact-resistant and ballistic structures) [7].

Multiaxial non-crimp fabrics (NCFs)

represent a modern class of textile reinforcements widely used in advanced composites. They consist of layers of fibers oriented in different directions (e.g.,  $0^\circ$ ,  $\pm 45^\circ$ ,  $90^\circ$ ), held together by a stitching thread without introducing significant fiber waviness (crimp). Their main advantage lies in the high mechanical efficiency, as the fibers remain nearly straight and can carry loads more effectively. Additionally, NCFs enable a more uniform and often reduced resin consumption, leading to better-controlled fiber volume fractions and improved mechanical properties. Manufacturing processes are generally faster compared to stacking multiple unidirectional plies, and handling is simplified due to the integrated multiaxial architecture. They also help reduce defects, such as voids or poorly impregnated regions. However, there are some drawbacks: drapability is lower, making them less suitable for complex geometries; production costs are typically higher than conventional woven fabrics; and the stitching thread can introduce local stress concentrations or influence interlaminar behavior, particularly in terms of delamination resistance [10].

In this context, our study focuses on the flexural testing of composites reinforced with biaxial glass fiber fabrics and an unsaturated polyester resin matrix. The novelty of the work lies both in the investigated material system, still relatively less explored compared to conventional composites, and in the systematic analysis of the influence of test rate and specimen thicknesses, on the flexural response.

## 2. Materials and Test Method

The reinforcement used in this study was a biaxial ( $\pm 45^\circ$ ) E-glass non-crimp fabric (NCF) with an areal density of 600-620 g/m<sup>2</sup> [11]. The fabric layers were held together by polyester stitching (Z-binding). Following a literature review on resins for glass fiber composites, the resin Enydyne H 68372 TA, together with the Metox-50W accelerator was selected [12], [13]. The composite

fabrication is similar to those presented in [2]. All materials were supplied by Rompolimer Composites [14].

The three-point bending configuration was selected because panel- and plate-type elements, typical of marine applications, are frequently subjected to bending in service. This loading condition simultaneously highlights the tensile response on back face and the compressive response on the front face, while also being sensitive to failure mechanisms and manufacturing defects, such as thickness non-uniformities, resin distribution variations, and regions with inconsistent impregnation.

The three-point bending tests were carried out using an Instron 5982 Universal Testing Machine [15], equipped with a 100 kN load cell, with a load measurement accuracy of  $\pm 0.5\%$  of the indicated value. The test procedure was performed on rectangular specimens, with a width of approximately  $28 \pm 2$  mm and a thickness ranging from 1.80 to 6.50 mm, depending on the number of biaxial fabric layers (4 layers (coded 4s), 6 layers (6s), and 8 layers (8s), respectively). During testing, the force  $F$  was applied at the mid-span of the specimen with a loading roller with radius  $R_1$ , while the specimen was supported on two fixed rollers with radius  $R_2$  ( $R_1 = R_2 = 5$  mm). The span length between supports was  $L = 100$  mm, and the total specimen length was approximately 280 mm. The span length, as well as the radii of both the support rollers and the loading roller, were kept constant for all tests to ensure the comparability of results.

For each bending test, the following mechanical properties were determined:

- the maximum flexural stress, corresponding to the maximum force,  $F_{max}$ :

$$\sigma_{max} = \frac{3 \cdot F_{max} \cdot L}{2 \cdot b \cdot h^2} \quad (1)$$

where:  $L$  – the span length between supports (kept constant at 100 mm for all tests),  $b$  – the specimen width, and  $h$  – the specimen thickness.

- maximum flexure strain for  $F_{max}$ :

$$\varepsilon_{max} = 6 \cdot \frac{d_{(F_{max})} \cdot h}{L^2} \quad (2)$$

where  $d_{(F_{max})}$  is the displacement corresponding to the moment when the force reaches its maximum value.

– the energy absorbed by the material up to the point where the force reaches its maximum value:

$$E_{(F_{max})} = 0.5 \cdot F_{max} \cdot d_{(F_{max})} \quad (3)$$

This formula represents an energy-based approximation, assuming a triangular area under the force–displacement curve. In reality, the experimental curve exhibits a more complex shape with a variable radius of curvature, and the method therefore provides a slightly underestimated value compared to the actual recorded energy. However, it remains sufficiently accurate for the evaluation of the mechanical behavior.

### 3. Analysis of the results

Figure 1 presents sets of 5 tested samples for the extreme test rate, 10 mm/min and 1000 mm/min, respectively. The visual analysis of the tested specimens highlights several important aspects regarding the damage mechanisms developed during bending.

As expected, an increase in damage severity under the loading roller is noticed with increasing composite thickness. Thicker laminates experience higher stress concentrations in the compression zone, leading to more pronounced local crushing and matrix damage. In contrast, the influence of the test rate on this type of damage appears to be less significant.

The sample lateral view reveals that higher test rates lead to a larger damaged area on the back (tensile side) of the samples. A similar effect is observed with increasing laminate thickness, where more extensive fiber breakage and interlaminar damage occur. This can be explained by the fact that thinner composites exhibit greater flexibility, allowing larger deformations before failure, while thicker laminates tend to fail earlier through more abrupt fiber fracture.

The damaged zone on the tensile side increases with laminate thickness, confirming that thicker specimens

accumulate more energy before failure and develop more extensive fracture regions. However, for specimens with the same thickness, no significant qualitative differences in damage morphology are observed between different test rates, suggesting that the loading rate mainly affects the failure kinetics rather than the failure mode itself.

In the region beneath the loading roller (compression side), the increase in damage with laminate thickness can be associated with local processes, such as micro-buckling of fibers and matrix crushing. Thicker laminates tend to develop higher through-thickness stresses and reduced ability to redistribute them, which promotes localized damage rather than gradual deformation.

Additionally, the contact between the roller and the specimen introduces a stress concentration that becomes more critical as stiffness increases. Since thicker laminates are stiffer, they exhibit reduced compliance, leading to more severe localized damage under the loading point.

On the tensile side (back face), the observed increase in damaged area with both thickness and test rate suggests that failure is governed primarily by fiber fracture and interlaminar cracking.

At higher test rates, the polymer matrix has less time to undergo viscoelastic deformation and energy dissipation, resulting in a more brittle response. This explains the larger and more abrupt damage zones observed in the lateral view at higher loading speeds. Furthermore, the increase in thickness leads to a higher bending stiffness, which reduces the curvature at failure but increases the stress level in the outer fibers. As a result, thicker laminates fail at lower strains but higher stresses, producing more extensive and sudden fiber breakage.

The biaxial ( $\pm 45^\circ$ ) non-crimp fabric architecture plays a role in noticed damage patterns. The  $\pm 45^\circ$  fiber orientation promotes shear-dominated deformation, which can delay crack initiation in thinner laminates by allowing some degree of stress

redistribution. However, as thickness increases, interlaminar stresses become more significant, favoring delamination between layers. The presence of stitching

threads may influence crack propagation paths, acting either as barriers or as stress concentrators depending on local conditions.

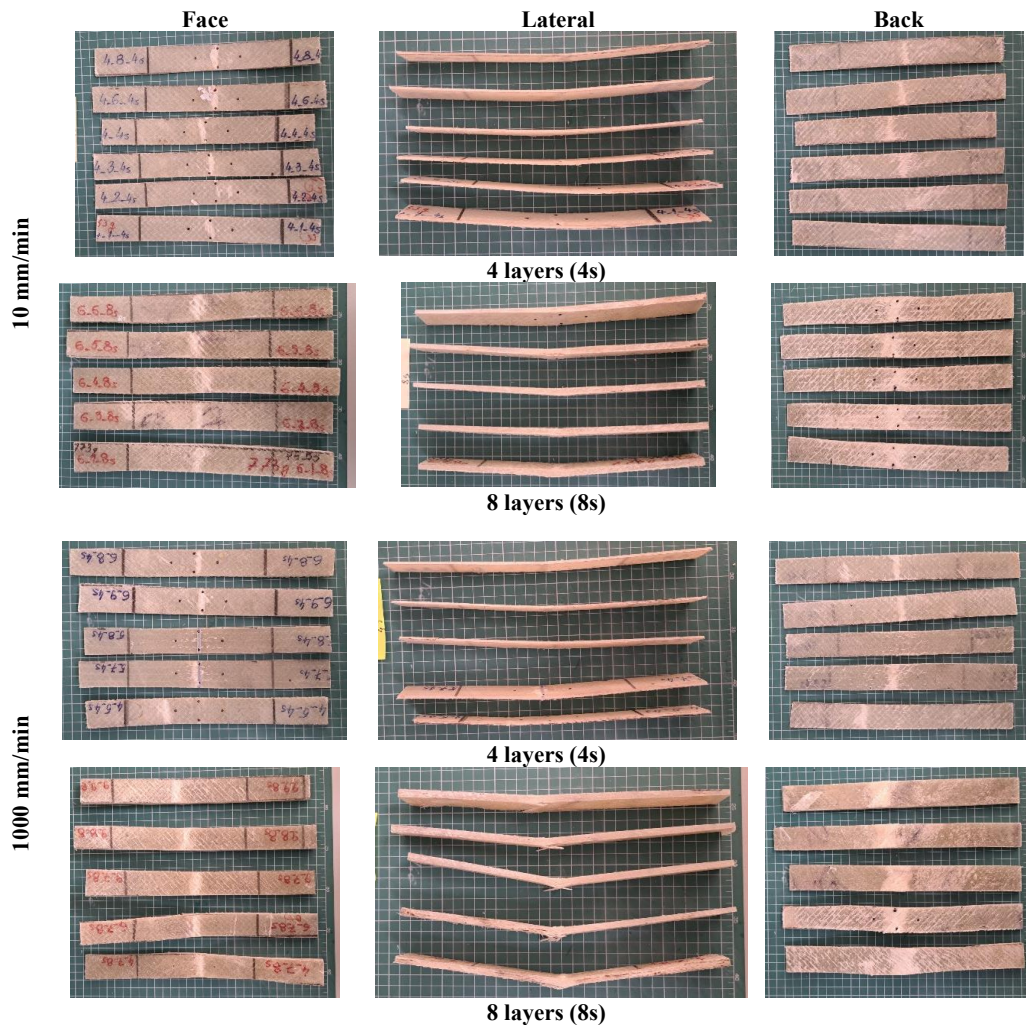


Figure 1. Aspects of the tested composites, for the extreme test rates (10 mm/min and 1000 mm/min, respectively)

Although no major qualitative differences in damage morphology are observed between specimens tested at different rates for the same thickness, this does not imply that the test rate has no effect. Instead, the loading rate primarily influences the kinetics of damage evolution and the peak stress levels, rather than the overall failure mode.

In other words, the same mechanisms (fiber breakage, matrix cracking, delamination) are active in all cases, but they occur more rapidly and with less energy dissipation at higher loading rates.

The results suggest that laminate thickness is the dominant parameter controlling the failure mode and damage extent, while the test rate mainly affects the rate-dependent response of the matrix and the abruptness of failure. This distinction is important for practical applications, where thickness can be optimized for strength and energy absorption, while loading rate effects must be considered in dynamic/impact conditions. Figure 2 presents the force–time curves obtained for the five tested specimens corresponding to each laminate thickness and each test rate. The plots were

represented using the same force scale on the Y-axis, while the time scale on the X-axis was adapted to the imposed test rate, in order to allow a clearer comparison of the force response. The curves generally exhibit three characteristic regions: an initial loading region, where the curves are relatively close to each other; a peak-load region, where the curvature changes more markedly as the maximum force is approached; and a post-peak region, where the curves become more scattered in both shape and force level, which is typical for composite materials due to progressive damage accumulation and non-uniform failure mechanisms. The maximum force increases with laminate thickness for all test rates, confirming the

higher load-carrying capacity of thicker specimens. This increase is particularly evident when comparing the 6-layer and 8-layer composites. In contrast, the influence of test rate on the maximum force appears to be less pronounced at the lower rates, namely 10 mm/min and 200 mm/min. More visible changes in the curve shape are observed at 500 mm/min and 1000 mm/min, where the response becomes sharper and the time required to reach the maximum force is strongly reduced.

For the thinner 4-layer composites, the force-time curves are relatively smooth at low and intermediate test rates, while a more rounded peak is noticeable mainly at 1000 mm/min.

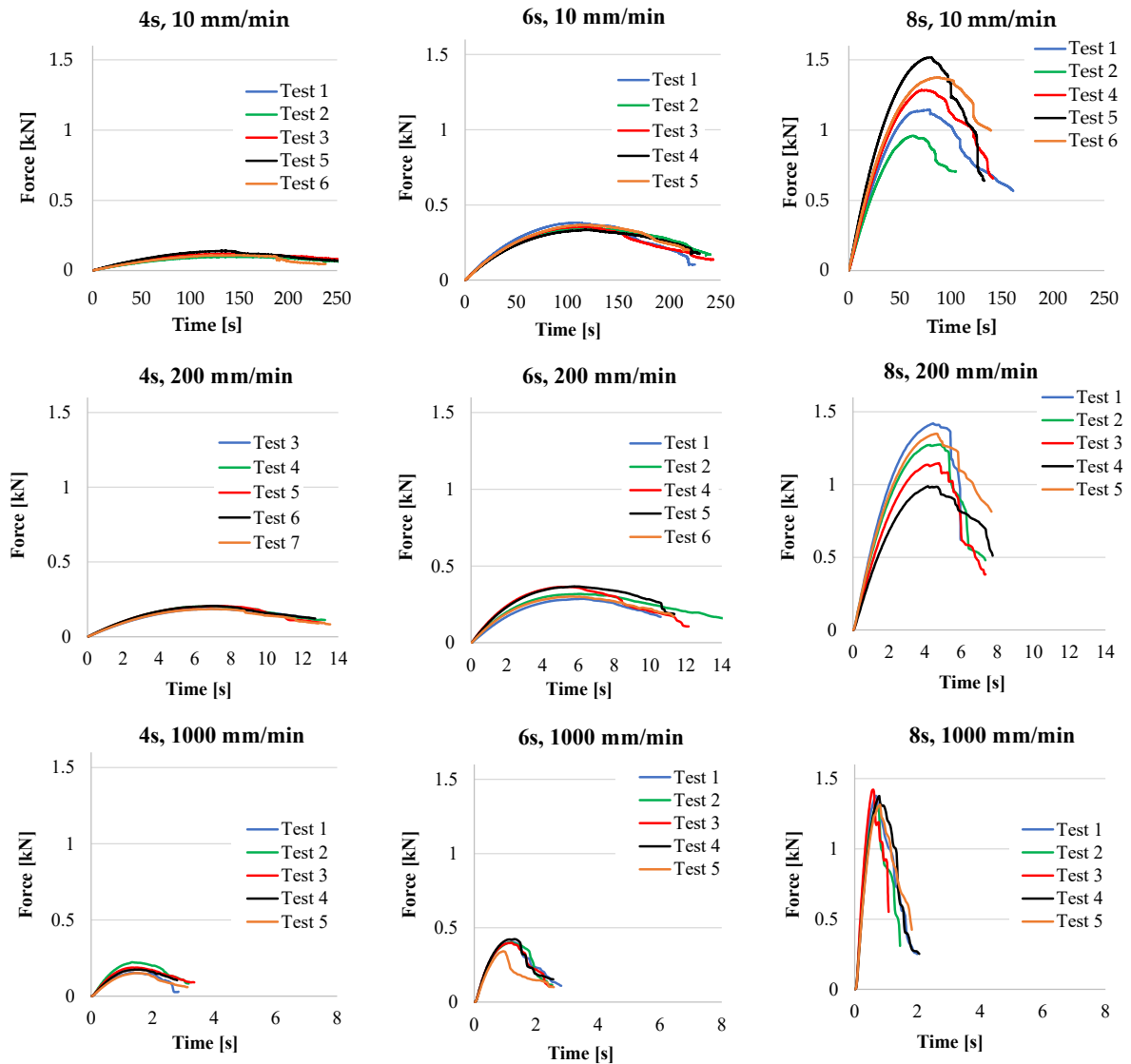


Figure 2: Force-time curves obtained during three-point bending tests for biaxial glass-fiber composite laminates with different numbers of layers and test rates.

For the 6-layer composites, this rounded peak shape appears already at 500 mm/min, whereas for the 8-layer laminates it is visible for all investigated test rates. This suggests that thicker laminates develop a more gradual damage process around the peak load, probably associated with internal fiber breakage, matrix cracking and interlaminar separation. At lower test rates (10 mm/min and 200 mm/min), the post-peak region is more extended and less uniform, indicating progressive damage evolution, commonly observed in composites.

Figure 3 presents flexural stress–strain curves for the tested composites. Compared with the force–time curves, strongly affected by both composite thickness and test rate, the flexural stress–strain curves exhibit a more similar general shape.

This indicates that the flexural response follows a comparable deformation pattern for all configurations. All curves show a clearly defined maximum flexural stress, followed by a post-peak region associated with progressive damage and failure development

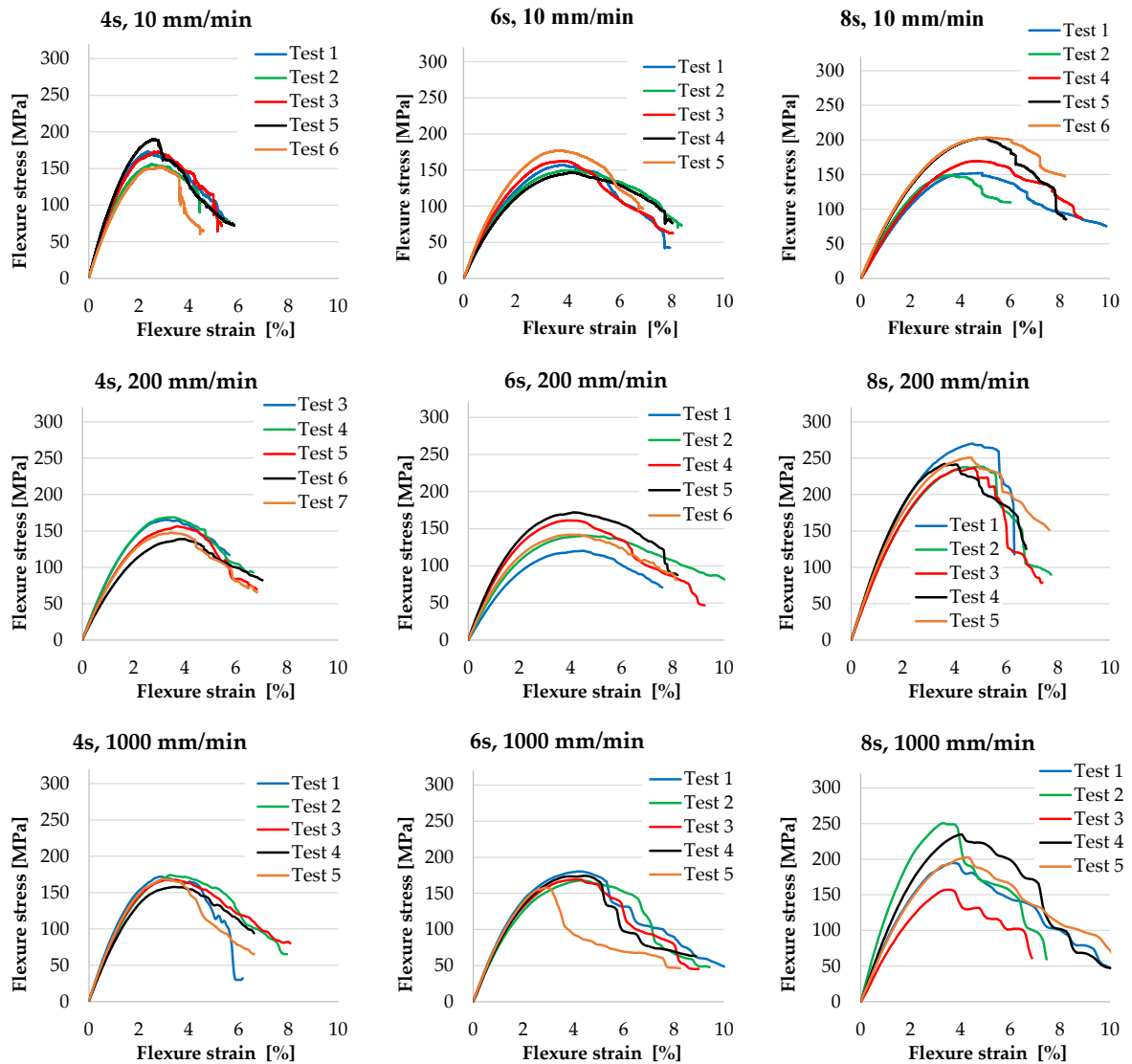


Figure 3: Flexural stress–strain curves obtained during three-point bending tests for biaxial glass-fiber composite laminates with different numbers of layers and test rates.

The tensile side, located on the face opposite to the loading roller, is particularly important because it is usually more sensitive to fiber breakage and layer separation.

The influence of test rate on the maximum flexure stress is limited at the lowest test rate. However, the maximum stress generally increases with laminate thickness. At 200 mm/min, the peak stress increases from about 150 MPa for the 4-layer laminate to about 250 MPa for the 8-layer laminate. A similar tendency is observed at 500 mm/min, where the 8-layer specimens reach the highest stress levels, approximately 260 MPa. At 1000 mm/min, the same thickness-related trend is maintained, although the maximum stress values are slightly lower than those obtained at 500 mm/min for the thicker laminates. This slight decrease may be associated with a more abrupt damage initiation and propagation. At very high test rates, the material has less time to redistribute stresses through progressive matrix cracking, fiber rotation, interlaminar sliding or gradual delamination. As a result, localized damage under the loading roller or on the tensile face may trigger earlier instability, leading to a lower peak stress compared with the 500 mm/min tests. Therefore, the effect of test rate should not be interpreted as strictly monotonic; in these composites, the response is governed by the combined influence of strain-rate sensitivity, laminate thickness, internal defects and progressive damage mechanisms.

Compared stress-strain curves with the force-time curves, which are strongly affected by both laminate thickness and test rate, the flexural stress-strain curves exhibit a more similar general shape. This indicates that, after normalization with respect to specimen geometry, the flexural response follows a comparable deformation pattern for all configurations. All curves show a clearly defined maximum flexural stress, followed by a post-peak region associated with progressive damage and failure development. The final stage of bending is characterized by a highly irregular, saw-

tooth-like response, with widely scattered curves. This behavior is typical of layered and fabric-reinforced composites and reflects the progressive accumulation of damage, including matrix cracking, fiber breakage, local delamination and frictional sliding between damaged layers.

The tensile side, located on the face opposite to the loading roller, is particularly important because it is usually more sensitive to fiber breakage and layer separation. The influence of test rate on the maximum flexural stress is relatively limited at the lowest test rate. However, the maximum stress generally increases with laminate thickness. At 200 mm/min, the peak stress increases from about 150 MPa for the 4-layer laminate to about 250 MPa for the 8-layer laminate. A similar tendency is observed at 500 mm/min, where the 8-layer specimens reach the highest stress levels, approximately 260 MPa. At 1000 mm/min, the same thickness-related trend is maintained, although the maximum stress values are slightly lower than those obtained at 500 mm/min for the thicker laminates.

This slight decrease at the highest test rate may be associated with a more abrupt damage initiation and propagation. At very high loading rates, the material has less time to redistribute stresses through progressive matrix cracking, fiber rotation, interlaminar sliding or gradual delamination. As a result, localized damage beneath the loading roller or on the tensile face may trigger earlier instability, leading to a lower measured peak stress compared with the 500 mm/min tests. Therefore, the effect of test rate should not be interpreted as strictly monotonic; in these composites, the response is governed by the combined influence of strain-rate sensitivity, laminate thickness, internal defects and progressive damage mechanisms.

For a designer, only the first region of the curves, almost linear, should be considered, together with an adequate safety factor. This region corresponds to a more predictable structural response, before the development of significant damage. The maximum force

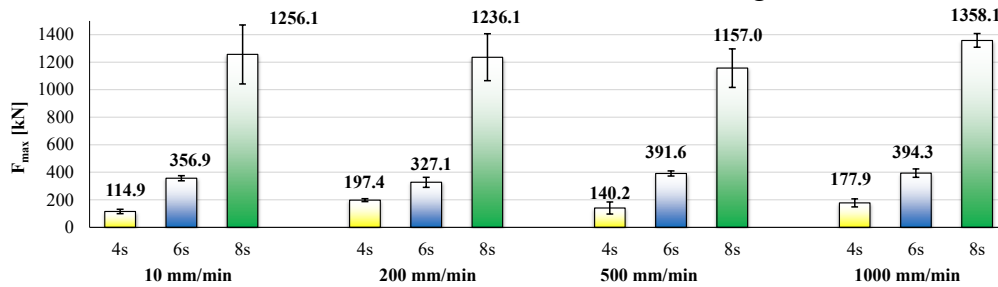
and maximum flexural stress are therefore more relevant for assessing the damage tolerance and energy absorption capacity of the material, particularly under severe loading conditions, such as collisions, impact events or drop-weight loading.

### 3.X. Synthesis of bending characteristics

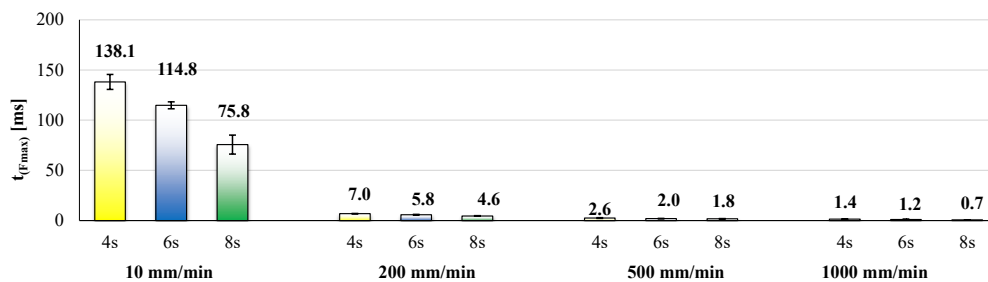
Figure 4 summarizes the main bending characteristics obtained from the experimental tests, as a function of laminate thickness and test rate. Unlike the previous figures, which present individual curves for each specimen, this figure allows a direct comparison of the average mechanical parameters and their standard deviations for a set of 5 tests under the same conditions (test rate and composite thickness).

The results show that laminate thickness has a stronger influence than test rate on most of the investigated characteristics, especially on maximum force, maximum stress, displacement at maximum force and absorbed energy.

a) The maximum force,  $F_{\max}$ , exhibits an accelerated increase with laminate thickness



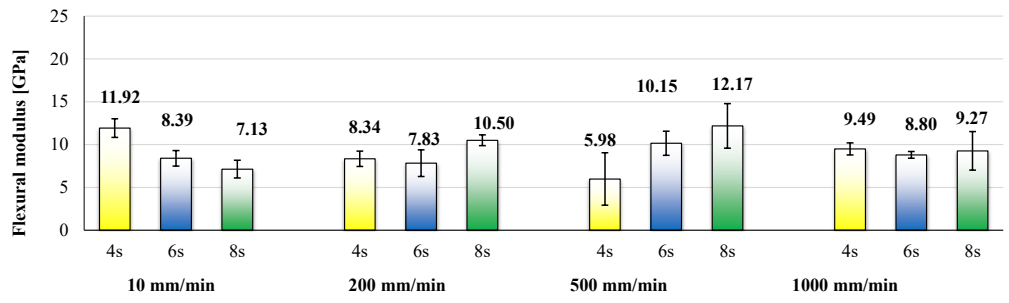
a)



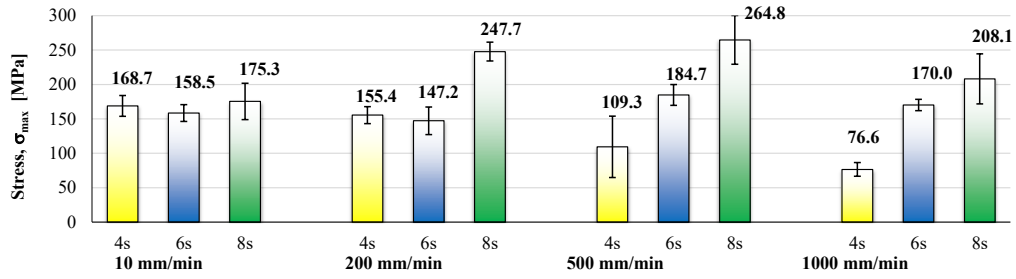
b)

within the investigated range. The average values show a moderate increase from 4 to 6 layers, followed by a much steeper increase from 6 to 8 layers. This behavior can be described by either an exponential-type or a power-law approximation, both giving similar fits for the available data. Therefore, the result should be interpreted mainly as evidence of a strong non-linear thickness effect within the tested laminate range, rather than as confirmation of a specific mathematical law.

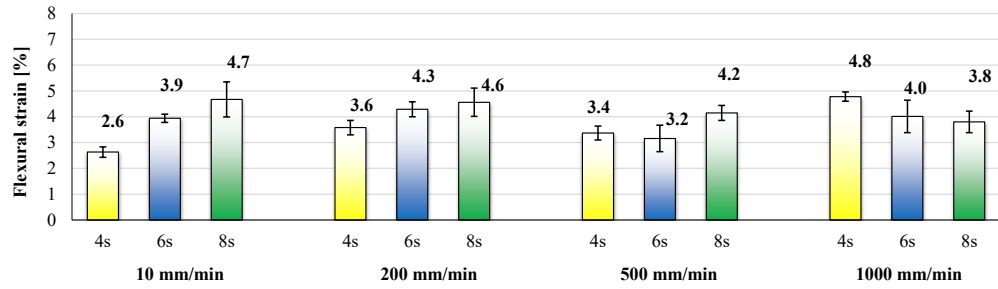
b) The time required to reach the maximum force,  $t_{(F_{\max})}$ , is much longer at the lowest test rate, 10 mm/min. As expected,  $t_{(F_{\max})}$  decreases sharply when the test rate increases, because the imposed displacement is applied over a much shorter time interval. This parameter is therefore mainly controlled by the test rate and only secondarily affected by laminate thickness. For the same test rate, thicker laminates tend to reach  $F_{\max}$  slightly earlier, but this influence is much less pronounced than the effect of loading rate.



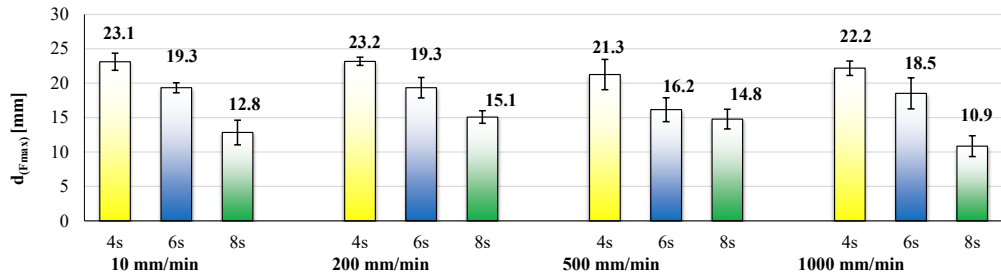
c)



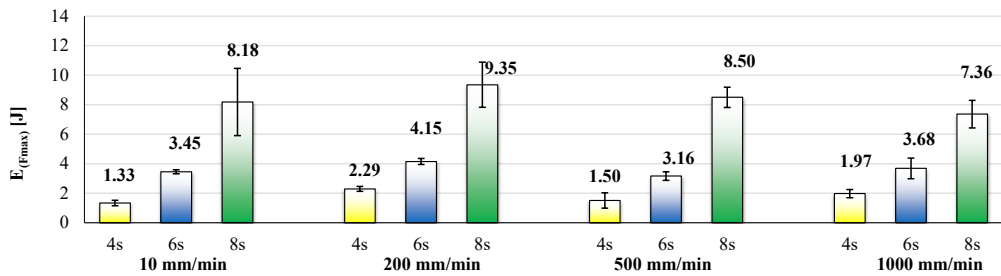
d)



e)



f)



g)

Figure 4. Characteristics of bending behavior of the tested composites, as function of number of layers and test rate

c) Flexural modulus exhibits a scattered variation and no clear monotonic trend with laminate thickness or test rate. This parameter is particularly sensitive to the initial slope of the flexural curve, which may be affected by specimen positioning, contact conditions, local thickness variation and the heterogeneous architecture of the fabric-reinforced laminate. Therefore, flexural modulus should be interpreted as an apparent flexural stiffness parameter. For conservative design purposes, a lower-bound modulus value, together with an appropriate safety factor, would be more appropriate than the average value.

d) The maximum flexural stress,  $\sigma_{\max}$ , is only weakly affected by laminate thickness at 10 mm/min, where the variation remains comparable to the experimental scatter. As the test rate increases, the thickness effect becomes more evident, especially at 500 and 1000 mm/min; however, the increase is not strictly proportional for all configurations. This may be related to local non-uniformities inherent to layered composite manufacturing, such as variations in fiber volume fraction, local resin-rich or resin-poor regions, small voids, fibre misalignment or stitching-related stress concentrations. Although the laminates were pressed at 0.5 MPa during manufacturing, such non-uniformities cannot be completely eliminated and may become more influential at high test rates, when damage initiation is more abrupt.

e) The flexural strain at maximum stress behaves differently for the two groups of test rates. At 10 mm/min and 200 mm/min, strain tends to increase with laminate thickness, probably due to a more progressive damage development and partial stress redistribution before failure. At 500 mm/min and 1000 mm/min, this dependence becomes weaker, with only a slight increase from the 4-layer to the 8-layer laminates, suggesting a more abrupt damage process at high loading rates. From a structural monitoring perspective, strain is an important parameter: by defining an allowable strain limit together with an appropriate safety factor, excessive

deformation could be detected in real time and preventive measures could be taken before severe damage occurs.

f) The displacement at maximum force,  $d_{(F_{\max})}$ , decreases consistently as the number of layers increases, indicating that thicker laminates reach their maximum load at lower bending deflections. This parameter is almost insensitive to test rate and is easier to measure directly than flexural strain, making it a useful experimental indicator of the deformation capacity of the tested laminates.

g) The energy absorbed up to the maximum force,  $E_{(F_{\max})}$ , is an important parameter for severe loading events, such as impact, collision or drop-weight loading. In this study, the absorbed energy was evaluated only up to  $F_{\max}$ , because the post-peak region is highly scattered and strongly dependent on the individual failure path of each specimen. Therefore, the energy absorbed after the maximum force should not be considered reliable for design purposes. The evolution of  $E_{(F_{\max})}$  is similar to that of  $F_{\max}$ , which is expected because the absorbed energy is directly related to both the maximum force and the corresponding displacement. The 8-layer composites absorb substantially more energy than the 4-layer and 6-layer laminates, confirming the beneficial effect of laminate thickness on damage tolerance. From an engineering point of view, this result is particularly relevant for marine structures. Although thicker composite laminates increase manufacturing cost and structural weight, they may be preferable for boat hulls or similar components where resistance to severe loading events and energy absorption capacity are critical.

#### 4. Conclusions

The experimental testing of composite materials remains essential, because different combinations of textile reinforcement, matrix resin and manufacturing conditions may lead to different mechanical trends. The biaxial  $\pm 45^\circ$  glass-fiber fabric investigated in this study proved to be sensitive to bending

loading, especially through the combined effects of laminate thickness and test rate.

A relevant aspect of this work is the analysis of several bending parameters, not only maximum stress and strain. Some parameters, such as  $F_{\max}$ ,  $\sigma_{\max}$ ,  $d_{(F_{\max})}$  and  $E_{(F_{\max})}$ , were clearly influenced by laminate thickness, while others, such as flexural strain and Young's modulus, showed weaker or more scattered dependence on the investigated factors.

Within the tested range, laminate thickness was the dominant parameter controlling the bending response. The thicker and less deformable composites exhibited higher

load-carrying capacity, higher maximum flexural stress and greater energy absorption up to  $F_{\max}$ . These parameters were also more clearly affected by the external loading conditions, especially at higher test rates.

The obtained maximum flexural stress values indicate that the tested composites may be suitable for lightweight marine structures, where bending resistance, damage tolerance and energy absorption are important design requirements. However, the results should be interpreted within the investigated thickness and test-rate ranges, and appropriate safety factors are required for structural design.

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