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Influence of Platelet Boundary Irregularity on the Nonlinear Mechanical Behavior of Platelet-Reinforced Composites

Djamel Batache, Abdennour Benhizia*, Abdelghani Khennab, Sarra Nacer

Mechanics of Structures and Materials Laboratory, University of Batna 2, Batna 05000, Algeria

Corresponding Author Email: a.benhizia@univ-batna2.dz

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ABSTRACT

Defects, such as cell wall thickness variations, significantly influence cellular materials' mechanical characteristics. For instance, during a compression test in deformation mode, the crush bands are initiated at cells with a thinner wall thickness. This paper examines the effect of boundary irregularity on the nonlinear elastoplastic mechanical behavior of platelet-reinforced composite materials. Two types of stochastic (random distribution) platelets: with rounded corners and with sharp corners are generated using the Voronoi tessellation method. To better compare the effect of boundary irregularity, the composites are analyzed for three different volume fractions. The microstructure of the composite studied consists of isotropic and linear elastic platelets embedded in a perfectly plastic elastic matrix. Nonlinear numerical simulation of the tensile test was carried out using FE Zebulon software. The results show that the composites exhibit bilinear stress-strain behavior, consisting of two lines representing, respectively, the linear behavior (whose slope is Young's modulus) and the plastic behavior (whose slope is the strain hardening modulus). The effective Young's modulus, yield strength, and tangent modulus of the composites are calculated and compared in terms of the shape and volume fraction of the platelets. In the elastic zone, the results indicate that the curves of the two types of stochastic platelets overlap, giving very close results for Young's modulus. In the plastic zone, the effect of platelet irregularity is noticeable. It has been found that the platelets with rounded corners have a higher tangent modulus than those with sharp corners. This deference can improve the composite's ability to withstand more deformation under high loads, unlike platelets with sharp edges.

1. INTRODUCTION

Due to their excellent performance, mechanical, and physical features, particle-reinforced composites inspired by natural architectures are being employed more and more in technology. Several types of inclusion shapes are studied to improve the mechanical properties of these materials, including simple shapes [1-4], that demonstrate a consistent rise in Von Mises stresses when the reinforcing particles change form from triangular to square, rhombic, pentagonal, hexagonal, and circular, respectively. Or complex shapes like aggregates [5, 6] in which the reinforcements significantly hinder the propagation of the stress wave and lessen the extent of damage to the concrete. In addition to the honeycomb shape [7, 8], which is used to control the deformation mode and improve the energy absorption.

The significant mechanical performance displayed by platelet composites, inspired by existing structures in nature, like nacre and bone, received massive attention from researchers. Miao et al. [9] conducted ballistic impact experiments on nacre-like composites made from aluminum alloy and epoxy resin. The researchers revealed that the nacre-like plates had superior ballistic performance compared to their comparable bulk plates, resulting in decreased residual velocity of the projectile. Wu et al. [10] conducted an experimental study to investigate the impact of brick aspect ratio and adhesive thickness on the fracture failure of 3D-printed nacre-like composites. The results revealed that the crack mostly propagated along the flexible adhesive in the specimen characterized by a tiny brick aspect ratio. However, the crack exhibited a greater inclination to penetrate the inflexible brick in the specimen with a large brick aspect ratio. Cui et al. [11] studied 3D-printed nacre-like structures exploring the influence of geometric parameters on mechanical behaviors under quasi-static in-plane compression tests. The results indicate that nacre-like materials exhibit four distinct phases in their quasi-static compression responses: elastic, plateau, fragmentation, and densification. Li et al. [12] examined bioinspired biomaterials with a brick-and-mortar microstructure. They have successfully created bioceramic composites of lamellar silicates with outstanding mechanical properties similar to cortical bone. This breakthrough overcomes the issue of the stress shielding effect caused by high-strength implant biomaterials. A review based on the dynamic properties of bio-inspired composite structural panels was presented by Zhang et al. [13]. The work demonstrates the excellent impact protection of bio-inspired structures for engineering applications.

The short platelet composites are characterized by high-volume fractions of reinforcement phase, and this makes the matrix walls thinner. Therefore, a variety of theoretical and numerical models have been developed to predict basic properties, based on the assumption that the matrix can be modeled with uniform wall thickness [14-21]. The presence of non-uniformity in cell wall thickness is a common characteristic seen in several natural cellular materials. Additionally, most commercially available metallic foams have some defects in their structures related to the procedure of elaboration.

The matrix cell wall thickness of platelet-reinforced composite depends on the shape of the platelet corners, the matrix cell wall thickness becomes uniform for sharp corners while it becomes non-uniform for rounded corners. This configuration can affect the mechanical behavior, especially in the non-linear regime, which was not addressed before.

By accounting for this effect on plastic behavior, engineers can design more efficient structures supporting a more significant load without adding too much weight.

For the aim of having better mechanical properties, it is still highly desired to investigate this design and compare it with the uniform one.

The main objective of this work is to study the effect of cell wall irregularity on the nonlinear elastoplastic mechanical behavior of platelet-reinforced composite materials. The paper is structured as follows:

- Section 2 describes the process of creating 3D platelet-reinforced composite models and the homogenization technique used to evaluate the mechanical behavior of the created composites.
- Section 3 presents the results of the modeling. Some concluding remarks are given in Section 4.

2. METHODOLOGY

2.1 Geometry and mechanical properties

The studied composite structure is designed in SolidWorks software, using the Voronoi tessellation method. This method is selected for its rapid and efficient modeling of random and irregular shapes, which closely resemble the natural microstructures of materials.

An image of a Voronoi polygons microstructure with sharp corners was converted to a 2D sketch and then extruded to create the 3D structure. The polygons with sharp corners are generated with 40 random distributed points which are considered as the number of seeds and a range of offsetting values between 0.057-0.239 mm is used to vary the volume fraction. The Voronoi polygons microstructure with rounded corners was obtained by applying the fillet function to the sharp corners with a consistent radius value of 2 mm. The matrix phase is obtained from a Boolean operation between the polygons and a rectangular parallelepiped.

This approach led to the creation of two different types of platelet composites in terms of matrix cell wall thickness, keeping the same size, volume fraction, and arrangement of the platelets, which offers suitable numerical models for comparison. To quantify the effect of the volume fraction, 3D models with three different volume fractions (Vf = 0.75, 0.80, and 0.85) of each platelet shape are designed as shown in Figures 1 and 2. The desired volume fraction was achieved by gradually increasing the cell wall thickness through varying the volume of the platelets using the Scale feature in SolidWorks software.

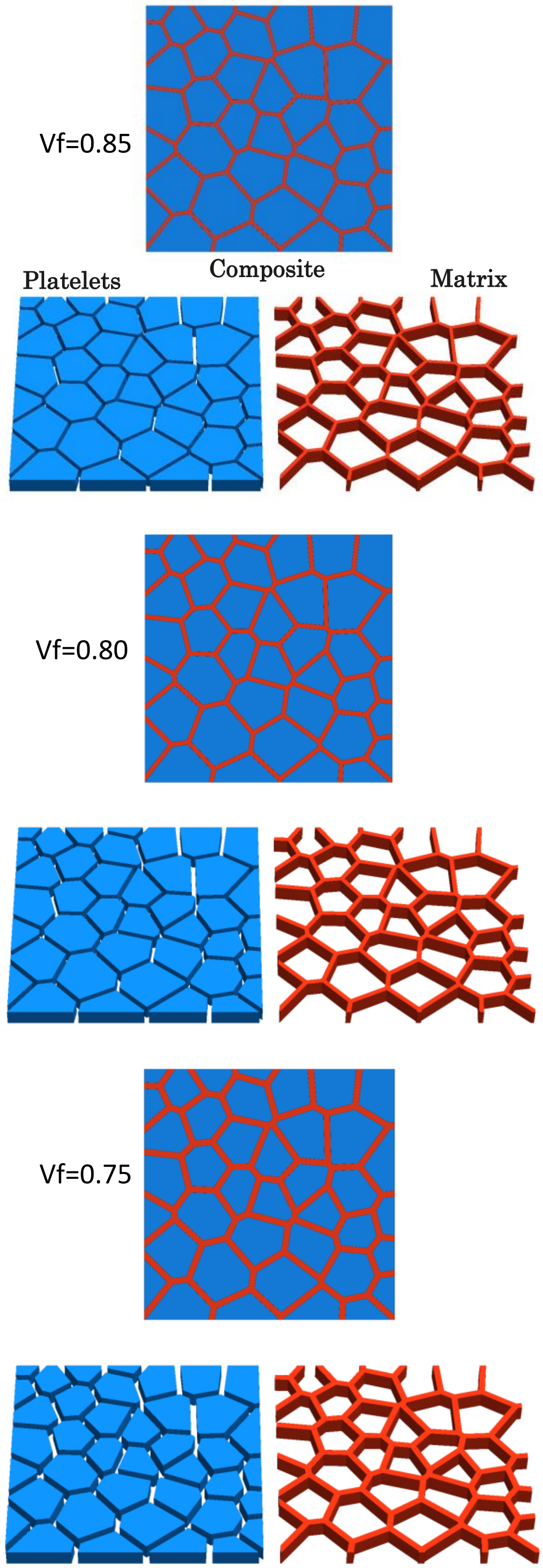

Figure 1. 3D Models of designed platelet-reinforced composite with sharp corners for three different volume fractions

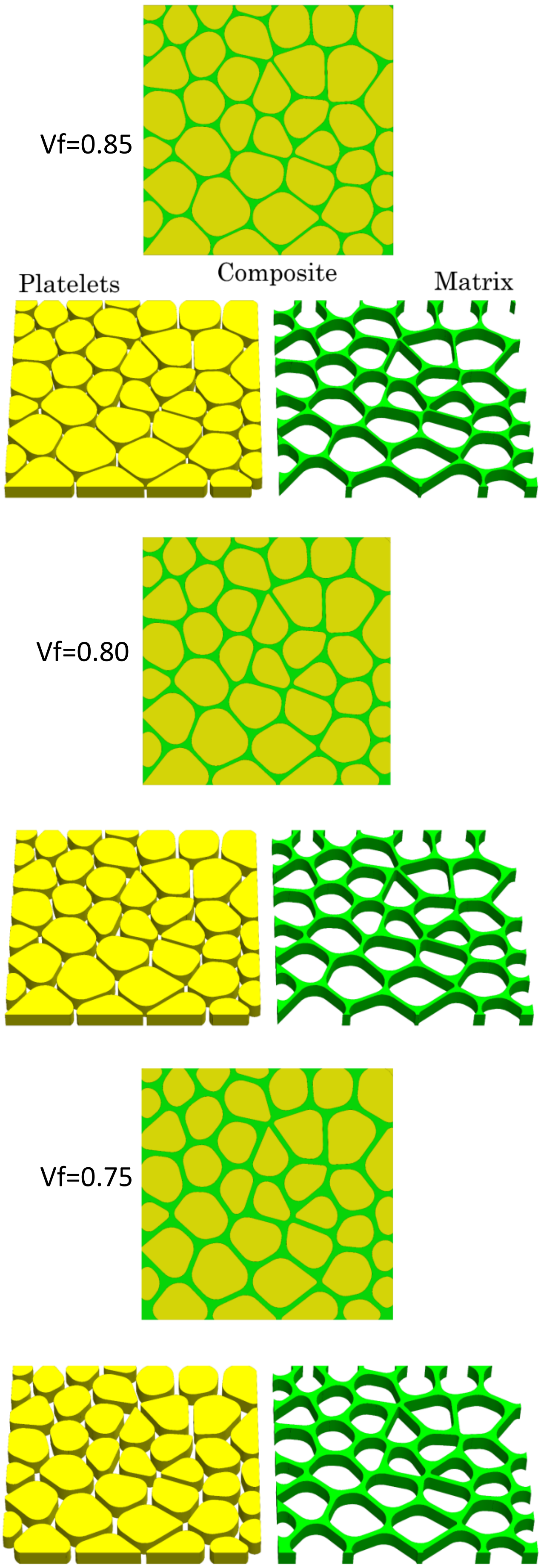

Figure 2. 3D Models of designed platelet-reinforced composite with rounded corners for three different volume fractions

The range of volume fractions in this study allows a comparison of the effect of non-uniformity on the matrix phase's cell wall thickness. The matrix becomes thick below the volume fraction Vf = 0.75, and the comparison becomes unreasonable.

As illustrated in Figure 3, the microstructure of the material considered is assumed to be composed of an aluminum matrix assumed to be elastic perfectly plastic with Young's modulus $E = 70000MPa$ and Poisson's ratio $\mu = 0.33$, and yield strength $\sigma_y = 117\ MPa$, containing isotropic and linear elastic carbon platelets with Young's modulus $E = 230000\ MPa$ and Poisson's ratio $\mu = 0.3$.

The carbon/aluminum composite is a very promising material in several areas due to its exceptional mechanical and physical qualities, as well as its lightness and superior resistance to corrosion.

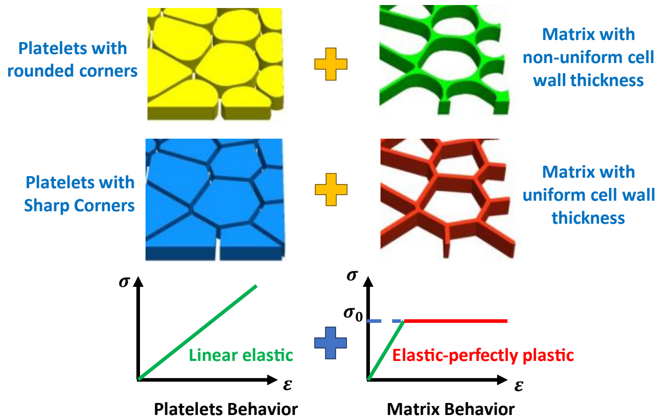

Figure 3. 3D models of platelet composites designed with two types of platelet shapes and the mechanical behavior of the constituents

2.2 Finite element analysis

To determine the macroscopic mechanical behavior of the designed composites, the 3D Models were subjected to uniaxial tensile loading by applying a prescribed displacement to one side of the structure while the other side was completely constrained as illustrated in Figure 4.

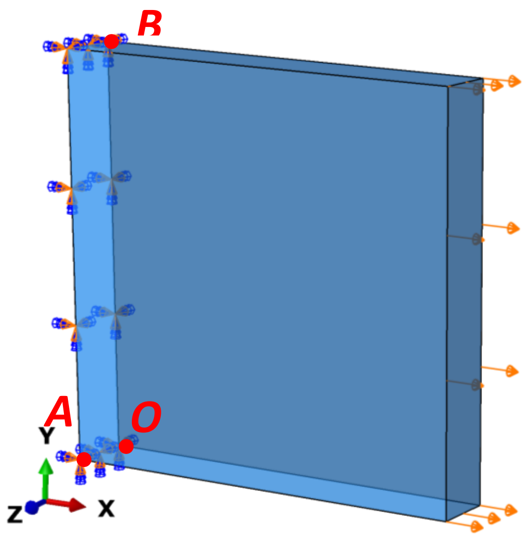

Figure 4. Schematic illustration of boundary conditions

The uniaxial tensile loading in the x direction is carried out as follows:

$$\begin{cases} u\{plane\ (x=0,y,z)\}=0 & v\{point\ O\ (0,0,0)\}=0 \\ u\{plane\ (x=l,y,z)\}=\delta & w\{point\ O\ (0,0,0)\}=0 \\ v\{point\ A\ (0,0,l)\}=0 & w\{point\ B\ (0,l,0)\}=0 \end{cases} \quad (1)$$

where, u, v, and w represent the displacements applied in the x, y, and z directions respectively, l denotes the length of the Representative Volume Element (RVE), and δ represents the prescribed displacement.

The created microstructure geometry was meshed with the tetrahedral solid element shape C3D10, due to its usefulness for meshing complex 3D geometries.

A mesh convergence study is conducted, which demonstrates that the minimum mesh size required for convergence is 0.45 mm. The mesh was executed automatically by the ANSYS software, Figures 5 and 6 show examples of the mesh that was used to perform the calculations.

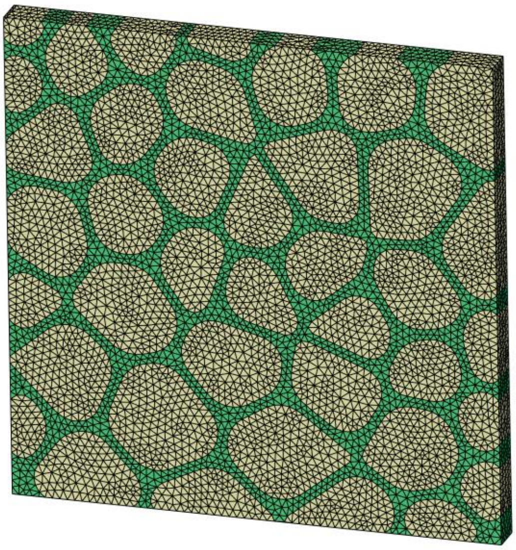

Figure 5. 3D finite element model of platelet-reinforced composite with rounded corners

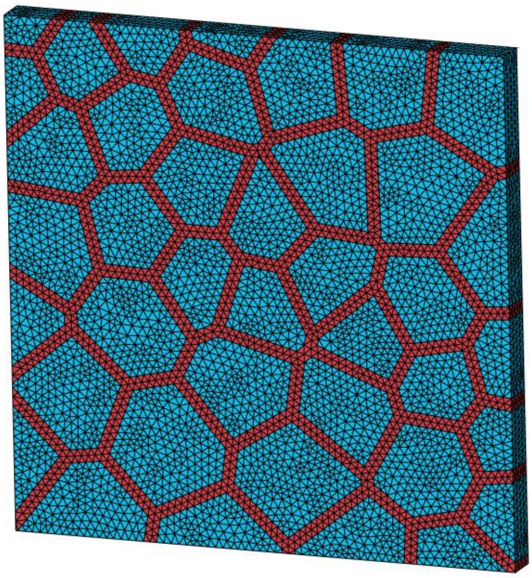

Figure 6. 3D finite element model of platelet-reinforced composite with sharp corners

3. RESULTS AND DISCUSSION

3.1 Stress-strain curves

The stress-strain curves obtained in uniaxial tension of the two tested configurations of the platelet's composites for three different volume fractions are given in Figure 7.

As shown from the curves, the overall tested composites exhibit bilinear stress-strain behavior.

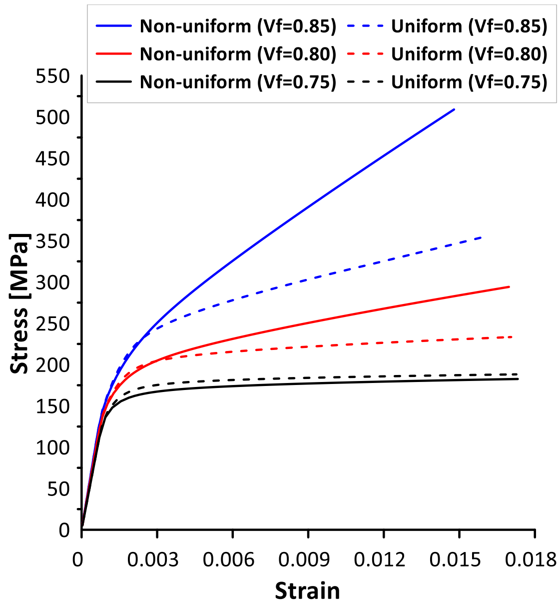

Figure 7. Comparison of obtained stress-strain curves of composites with two different platelet shapes, and three different volume fractions

As can be seen in the figure, the results of the two types of stochastic platelets perfectly matched in the elastic zone, while the effect of irregularity of the cell walls appears significantly in the plastic zone. The platelets with rounded corners have a higher tangent modulus than the ones with sharp corners.

3.2 Effective mechanical properties

For a comprehensive comparison, the effective mechanical properties used to describe the stress-strain curve of the two studied shapes, are determined and compared for each volume fraction.

3.2.1 Effective Young's modulus

The effective Young's modulus E^{eff} is determined from the slope of the linear part of the obtained strain–stress curve.

The results of the calculated effective Young's modulus of the tested composites with two different platelet shapes, and three different volume fractions are compared in Table 1.

Table 1. Effective Young's modulus

Volume Fraction (%)	Young's Modulus (MPa)	
	Platelets with Rounded Corners	Platelets with Sharp Corners
0.75	159294.11	159513.59
0.80	173388.82	173328.13
0.85	183454.35	183391.17

The determined values of Young's modulus are compared in the diagram presented in Figure 8. The two types of stochastic platelets provide very close results and this is confirmed for three volume fractions.

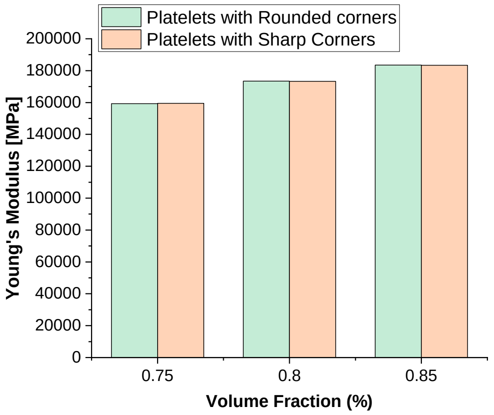

Figure 8. Comparison of effective Young's modulus of the tested composites with two different platelet shapes, and three different volume fractions

3.2.2 Effective yield strength

The yield strength σ_y^{eff} is determined by the 0.2% offset strain method. The results for the tested composites with two different platelet shapes and three different volume fractions are compared in Table 2.

Table 2. Effective yield strength

Volume Fraction (%)	Yield Strength (MPa)	
	Platelets with Rounded Corners	Platelets with Sharp Corners
0.75	167.6	175.74
0.80	207.22	205.64
0.85	263.02	249.14

The comparison of the determined effective yield strength is presented in Figure 9. The two types of stochastic platelets provide the same results and this is confirmed for three volume fractions.

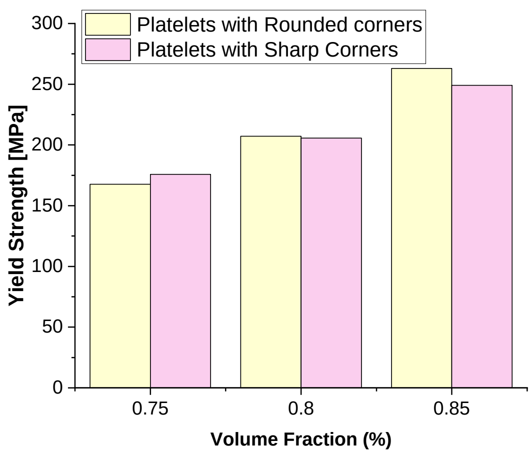

Figure 9. Comparison of effective yield strength of the tested composites with two different platelet shapes, and three different volume fractions

3.2.3 Effective Tangent modulus

The effective Tangent modulus E_T^{eff} is determined from the slope of the second linear part (after the yield strength point) of the obtained strain–stress curve.

The results of the calculated effective Tangent Modulus of the tested composites with two different platelet shapes, and three different volume fractions are reported in Table 3.

Table 3. Effective Tangent modulus

Volume Fraction (%)	Tangent Modulus (MPa)	
	Platelets with Rounded Corners	Platelets with Sharp Corners
0.75	908.93	760.11
0.80	6137.51	1763.60
0.85	21524.08	7405.19

The results of effective Tangent modulus are compared as presented in Figure 10, the effect of irregularity of the cell walls appears significantly in the plastic zone. The platelets with rounded corners have a higher tangent modulus than the ones with sharp corners. The difference increased as the volume fraction increased.

The effective tangent modulus of the tested composite material is related to the shape of the matrix cell wall. When the volume fraction is high, the cell wall becomes non-uniform and thinner in the middle compared to a uniform cell wall. This non-uniformity reduces the effect of the perfectly plastic elastic behavior of the matrix phase and causes the composite material to behave more elastically.

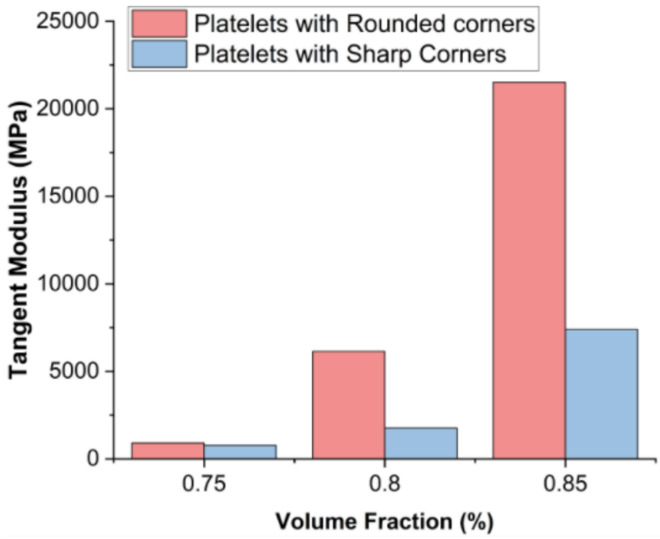

Figure 10. Comparison of effective Tangent Modulus of the tested composites with two different platelet shapes, and three different volume fractions

Based on the results obtained, it has been observed that platelets with rounded corners have a higher tangent modulus in comparison to those with sharp corners. This indicates that the material with rounded corners offers more resistance to deformation under high loads than platelets with sharp corners.

4. CONCLUSIONS

Most current methods for platelet-reinforced composite optimization simulate the microstructure using a matrix with uniform cell wall thickness rather than comparing it to the situation of a non-uniform matrix. In this study, platelet-reinforced composite materials were made with non-uniform thickness, and their mechanical characteristics were compared to those of microstructure with uniform thickness. The effect of cell wall irregularity was investigated by calculating the nonlinear elastoplastic mechanical behavior of an elastic perfectly plastic matrix, containing isotropic and linear elastic platelets. The homogenization technique is used to predict the effective properties of the created composites.

The advantage of the homogenization technique based on the finite element method is that it can recover the homogeneous behavior of the constituents. In the study, the perfectly plastic elastic behavior of the isotropic matrix was recovered by neglecting the platelet volume fraction, and the linear elastic behavior of the platelets was recovered by ignoring the matrix volume fraction.

The mechanical behavior is evaluated by the finite element method using the software ZEBULON. Based on the obtained results, the following conclusions can be drawn:

- Under uniaxial tension, the created composites exhibit bilinear stress-strain behavior.
- Within the elastic zone, the findings demonstrate that the curves of the two categories of stochastic platelets coincide, yielding highly similar outcomes for Young's modulus.
- The effect of irregularity of the cell walls appears significantly in the plastic zone. The difference increased as the volume fraction increased.
- The relationship between the shape of the matrix cell wall and the effective tangent modulus of the tested composite material is significant. At large volume fractions, the cell wall exhibits non-uniformity with a thin center section compared to the uniform one. This non-uniformity diminishes the impact of the matrix phase's completely plastic elastic behavior and results in the composite material exhibiting a more elastic response.
- Rounded corner platelets have a higher tangent modulus than sharp corner platelets, which can improve the composite's ability to withstand deformation under high loads.

One of the main limitations of this study is the difficulty in modeling composites that have a volume fraction larger than 0.85. This is because the cell wall of the matrix becomes thinner, making it harder to capture with standard mesh resolution. Additionally, characterizing the global structure of the composites requires significant computational time, especially when examining large loads. As a result, the analysis is often restricted to smaller samples.

The platelet-reinforced composite has the potential to be an effective material for energy absorption. Further studies are recommended for integrating the structure into an energy-absorbing device.

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NOMENCLATURE

E	Young's modulus, MPa
Vf	Volume fraction
E^{eff}	Effective Young's modulus, MPa
E_T^{eff}	Effective Tangent modulus, MPa

Greek symbols

σ_y^{eff}	yield strength, MPa
μ	Poisson's ratio