Relationship between elastic properties and energy absorption of different types of aramid and UHMWPE composites used in ballistic protection

DOI: 10.35530/IT.075.04.2023137

ALİ ARI MEHMET KARAHAN

ABSTRACT – REZUMAT

Relationship between elastic properties and energy absorption of different types of aramid and UHMWPE composites used in ballistic protection

This study aimed to analyse composite materials' mechanical and elastic properties from various aramid and ultra-high-molecular-weight polyethylene fabrics used in ballistic armour materials. Furthermore, a comprehensive analysis was conducted to examine the correlations between the energy absorption data acquired from the low-velocity impact, dynamic compressive, and ballistic impact V50 tests performed in our prior investigations and the tensile test outcomes of these composites. The research revealed a notable correlation between Poisson's ratio, elasticity modulus values, and energy absorption capability. The composite material with the lowest Poisson ratio exhibited superior energy absorption performance in all tests. Composites reinforced with unidirectional textiles have attracted attention due to their low Poisson ratio and high elasticity modulus values, resulting in exceptional energy absorption capability.

Keywords: *elastic properties, aramid, UHMWPE, ballistic, Poisson's ratio, auxetic structure*

Relația dintre proprietățile elastice și absorbția de energie a diferitelor tipuri de compozite cu fibre aramidice și UHMWPE utilizate în protecția balistică

Acest studiu și-a propus să analizeze proprietățile mecanice și elastice ale materialelor compozite realizate din diverse țesături din fibre aramidice și polietilenă cu masă moleculară foarte ridicată utilizate în producerea materialelor de blindaj balistic. Mai mult, a fost efectuată o analiză cuprinzătoare pentru a examina corelațiile dintre datele de absorbție a energiei obținute din testele V50 de impact la viteză redusă, compresiune dinamică și impact balistic efectuate în investigațiile noastre anterioare și rezultatele testelor de tracțiune ale acestor compozite. Studiul a evidenţiat o corelație notabilă între coeficientul lui Poisson, valorile modulului de elasticitate și capacitatea de absorbție a energiei. Materialul compozit cu cel mai scăzut coeficient al lui Poisson a prezentat performanțe superioare de absorbție a energiei în toate testele. Compozitele armate cu materiale textile unidirecționale au atras atenția datorită coeficientului lui Poisson scăzut și valorilor ridicate ale modulului de elasticitate, rezultând o capacitate excepțională de absorbție a energiei.

Cuvinte-cheie: *proprietăți elastice, aramidă, UHMWPE, balistic, coeficientul lui Poisson, structură auxetică*

INTRODUCTION

High-performance fibres and their fabrics, such as aramid and ultrahigh molecular weight polyethylene (UHMWPE), are widely used in personnel armour systems against exploding ammunition fragments, such as protective helmets and armour panels [1–5]. Manufacturers often utilize these fibres as reinforcement in the form of continuous filaments or woven fabric embedded in a resin [6]. Considering the nature of the fibres, a high fibre volume ratio was chosen to maximise the ballistic performance of the composite materials [5–8].

The behaviour of composite materials under high-velocity impact loading is complex and needs to be better understood. The structure of the reinforcing fabric makes this situation even more complicated. Because composites are inherently complex and few studies exist, looking at reinforcement fabrics from different angles can make them more resistant to impact. Textile reinforcement is critical in composite materials, as it profoundly affects their mechanical and impact performance. The type of reinforcement fabric, weave type, and Poisson's ratio are critical determinants of the composite's impact performance. These different parameters allow us to create ballistic materials with a high strength-to-weight ratio and energy absorption performance optimised for ballistic applications. The primary functions of reinforcement in composite materials include distributing applied impact or mechanical forces and providing protection against external forces. It is possible to achieve high-impact resistance by choosing the right combination of matrix material and fibres [9].

Optimizing the layers of ballistic composite materials maximizes the energy absorption performance. Reinforcements can be divided into three forms according to their structure: unidirectional structures (UD), two-dimensional structures (2D), and three-dimensional structures (3D) [10]. Furthermore, two main types of reinforcement materials in ballistic applications are para-aramid and UHMWPE [11]. Para-aramid fibres, like Kevlar, offer remarkable tensile strength and resistance to impact. Certain UHMWPE fabrics, such as unidirectional (UD)

Dyneema provide exceptional strength and rigidity in the direction of the fibres. Additionally, they have exceptional strength relative to their weight and exhibit remarkable impact absorption capabilities, making them ideal for lightweight ballistic armour applications [12]. Some researchers are studying the effect of UD reinforcement on the mechanical and impact properties of composites (such as) Barhoumi et al., investigating the mechanical properties of fibres and fabrics used in ballistic protection [13]. Bajya et al. investigated the effectiveness of soft armour panels for ballistic protection. They tested these panels at a speed of 430 m/s and against 9 mm bullets. UHMWPE UD reinforced panels have been replaced with woven fabric-reinforced panels [14]. While 2D-woven composite materials have outstanding strength-to-weight ratios and can be easily shaped into complex forms, they have limitations, including poor impact properties. Some researchers, such as Zhou et al., studying the effect of 2D woven composites on mechanical and impact properties stated that knitting models significantly affect parameters such as stress-strain curves and Poisson's ratio. Lower crimp ratios were associated with linear stress-strain curves and higher strength and elasticity, while higher crimp ratios exhibited nonlinear behaviour. They concluded that the crimp ratio directly affects flexibility, strength, and Poisson's ratio [15]. Lopresto et al. investigated the mechanical properties of 2D-woven plain and twill-woven fabrics made of basalt fibre. According to this study, plain weaving is better than twill weaving for tensile and bending strength because it has a more compact structure. However, twill weaving is better than plain weaving for energy absorption performance, such as fracture toughness and shear strength, because it has reduced waviness/lower crimp [16].

Poisson's ratio, another parameter determining energy absorption performance, is the ratio of lateral stress to longitudinal stress in axial tension [17]. Poisson's ratio can be positive or negative. Auxetic structures have a negative Poisson's ratio. A material with a Poisson's ratio close to 0 is considered nearly incompressible [18]. The negative Poisson's ratio shows that the material expands in the lateral direction at the beginning of the axial force on the material. The auxetic structure of these reinforcing elements makes them expand when they are under tension. They have advanced mechanical properties like high impact resistance, better tensile strength, and better energy absorption [19]. Moreover, with their extraordinary expansion capacity under sudden dynamic forces, the energy absorption of composites increases significantly. Due to all these features, auxetic structures are highly desirable in ballistic armour applications, where dynamic impact resistance is significant [20]. Some researchers who studied the effect of Poisson's ratio on the impact properties of composites: Li et al. They investigated the impact of auxetic structures by comparing non-auxetic and auxetic structures. They measured modulus, energy absorption and hardness values with various mechanical tests. The study showed that auxetic structures exhibit high modulus [21]. Zhou et al. performed repeated low-speed drop-weight impact tests on textile-based composites. When compressed statically, the non-auxetic structure composite is much softer and absorbs less energy than the auxetic structure composite. However, during the impact test, the auxetic textile composite increases its maximum negative Poisson ratio value, resulting in higher energy absorption performance [22]. Hassan et al. investigated the effect of auxetic structures on impact resistance using different types of yarns and showed that the difference in woven structures had a significant effect on impact energy. Auxetic results concluded that if the pattern of binding yarn and ground weave has the same float length, then the structure will have higher auxetic. Secondly, the higher float length also significantly affects the auxetic of the structure [23]. A study by Alderson et al. compared textile-based auxetic and non-auxetic structures. They discovered that auxetic structures were better at absorbing energy and resisting impacts when put under compressive force than non-auxetic structures [24]. According to Steffens et al., auxetic structures exhibit outstanding impact performance, making them suitable for protective applications [25]. Liaqat et al. compared auxetic-reinforced composites with non-auxetic-reinforced composites. The study found that the composite with woven auxiliary material had 2.72 J more impact energy than the reinforced composite sample without [26].

Various studies have investigated the mechanical properties and ballistic performance of ballistic fibres and composites. Before discussing the impact properties of composites, it is necessary to understand their deformation behaviour and mechanical properties. Previous studies in the literature have yet to find a comprehensive relationship between the mechanical properties of aramid and UHMWPE composites and their ballistic protection and energy absorption properties. Our previous studies investigated the energy absorption properties [1, 2, 6, 7, 27] and ballistic protection properties [28] of various aramid and UHMWPE fabric composites. The mechanical and elastic properties of thermoplastic composites made from different aramid and UHMWPE fabrics used to make ballistic protective composites were looked into in these studies. So, this study aims to investigate how the mechanical and elastic properties of different aramid and UHMWPE composites used for ballistic protection relate to the energy-absorbing properties achieved with these materials.

MATERIALS AND METHODS

Materials

Six different ballistic fabrics, whose properties are given in table 1 and whose structures are shown in figure 1, were used as reinforcement and nolax A21.2007 low-density polyethylene (LDPE) adhesive film (density 0.94 g/cm^3, melting temperature 80–90 °C and melt flow rate of 6–9 g/10 min) was used as a

Table 1

PROPERTIES OF REINFORCEMENTS USED IN THE STUDY

Reinforcement type	Reinforcement code	Reinforcement producer	Weave type	Linear density of Warp/Fill yarns (Tex)		Warp/Fill (or 0°–90°) yarns		Yarn density (yarns/m)	Areal density (y/m^2)	Crimp Warp/Fill (%)	Reinforcement thickness (mm)
				Warp	Fill	Warp	Fill				
Aramid woven fabric-CT 736	R_1	Teijin	2×2 Basket weave	336/	336	Twaron 2000	Twaron 2000	127/127	410	0.8/0.8	0.6
Aramid woven fabric-Artec	R_2	Pro-System	1×1 Plain weave	58/	58	Artec	Artec	116/116	135	0.2/0.2	0.23
Aramid Bi-Axial non-crimp fabric-XA450	R_3	Saertex	Bi-axial non-crimp	336	-	Twaron 2000		127/127	465	Non-crimp	0.40
Aramid UD GS3000	R_4	FMS	UD	126	-	Kevlar 49/Kevlar 49		-	510	Non-crimp	0.50
UHMWPE UD Dyneema H62	R_5	FMS	UD	176	-	Dyneema SK62		-	262	Non-crimp	0.25
UHMWPE UD Dyneema H5T	R_6	FMS	UD	176	-	Dyneema SK62		-	235	Non-crimp	0.25

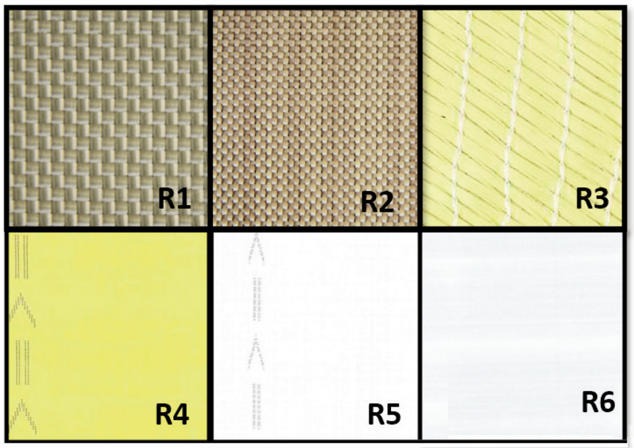

Fig. 1. Ballistic fabrics used as reinforcements

matrix system. The properties of fibres, which were used in the preparation of reinforcement structures, are given in table 2.

Table 2

PARAMETERS OF THE ARAMID AND UHMWPE FIBRES USED IN THE STUDY

Parameters	Twaron 2000® (Aramid)	Kevlar 49® (Aramid)	Dyneema SK62® (UHMWPE)	Artec® Russian Aramid
Young modulus (GPa)	85	112	113	103
Strength (cN/Tex)	235	208	338	181
Ultimate elongation (%)	3.5	2.4	3.6	2.8
Density (g/cm^3)	1.44	1.44	0.97	1.44

Composite manufacturing

The ballistic fabrics were cut to a size of 500 mm × 500 mm and composite laminates were prepared, with the same number of fabric layers and different panel thickness, different fabric layers and same panel thickness, different orientations of fabric layers and same panel thickness and different number of fabric layers and different panel thickness, using the autoclave process. The temperature of the process was kept at 110°C and the pressure of the vacuum to 14.8 bar (table 3). Figure 2 shows the different stages of the manufacturing process.

Determination of the elastic properties of composite materials

This section determined the tensile modulus, extension ratio, and Poisson's ratio values of composite materials under static tensile loading. The materials, test methods, and measurement systems used in the tests are presented below. Measurement of the above properties is crucial for accurately modelling the materials used. Only materials that passed the

Table 3

PROPERTIES OF THE COMPOSITE PLATES USED IN THIS STUDY

Sample code	Reinforcement type	Reinforcement layer number	Stacking direction	Resin	Plate thicknesses (mm)	Volume fraction (V_f)	Areal weight (g/m^2)
C1	R1	8	0°/90°	LDPE	4.1±0.23	55.56	3790
C2	R2	12	0°/90°		3.8±0.39	59.61	2130
C3	R3	8	45°/–45°		3.8±0.45	67.98	4230
C4	R4	8	0°/0°		3.9±0.25	72.65	4590
C5	R5	12	0°/0°		3.8±0.40	78.13	3390
C6	R6	12	0°/0°		3.8±0.50	78.13	3390

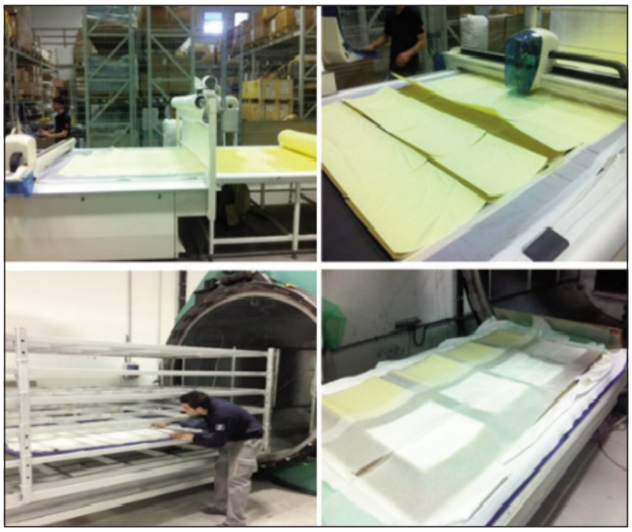

Fig. 2. Different stages of composite manufacturing process

preliminary screening were used in these tests. Tensile tests were carried out with Besmak-BMT 100E brand Universal Tensile Tester (100 kN). The samples for the tensile test were prepared according to TS EN ISO 527 standards. The tensile speed and the pre-stress value were set as 2 mm/min and 10 N, respectively. The measuring length was 50 mm video extensometer and the test conditions were carried out at 21°C. Tensile tests were carried out at the Bursa Technology Coordination and R&D Center (Bursa, Türkiye).

Measurement system

Each type of composite sample is assigned a code, and researchers determine all results based on these codes. The researchers conducted the testing of samples using the MTS Bionix II axial testing system (figure 3) available in the laboratory. The researchers recorded strain values from the surfaces of the samples using optical methods and calculated them using Vic3D software. For each loading case, special software matched the optical strain values and force values. This made it possible to calculate and plot the tensile modulus, the Poisson's ratio (equation 1), and the tensile (stress-strain) curve.

$$\nu = -\Delta T/\varepsilon_{yy} \qquad (1)$$

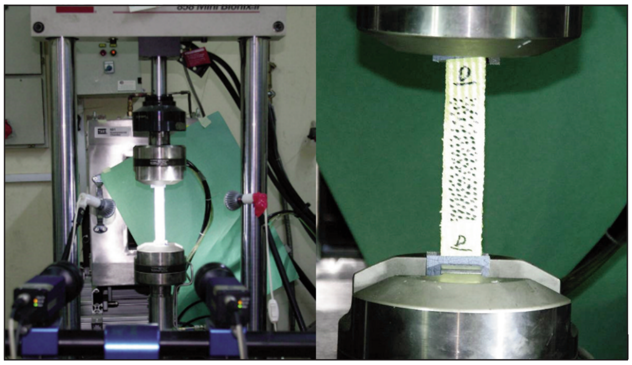

Fig. 3. MTS Bionix II Axial test system

In the above equation, ν is the Poisson's ratio, ΔT represents the change in thickness, and ε_{yy} represents the axial stress.

Results and discussion

Figure 4 and table 4 present the tensile test results of composite samples. According to these graphs, the tensile-strain curves showed a very similar character. A different character is seen only in the C3 sample. This is because there is a 45° angle between the tensile direction and the fibre direction in the C3 sample. All other samples exhibited a fairly linear tensile curve. According to the test results, C2 has the highest, and C3 composite has the lowest tensile strength value. When evaluating aramid composites among themselves, C2 exhibits a tensile strength value 4.2 times higher than C1 and 2.3 times higher than C4. When UHMWPE composites are evaluated among themselves, C5 exhibits a tensile strength that is 1.02 times higher than that of C6. C2, reinforced with aramid fibre, exhibits a strength value 1.3 times higher than C5, reinforced with UHMWPE.

A material with a high tensile modulus is more rigid and less deformed. This may affect the material's energy absorption performance under impact or load. Materials with a higher modulus suffer less deformation and have higher energy absorption performance [29]. In this context, Table 4 shows that C4, C5, and C6 modulus values are the highest, with no significant difference between them. C5 has the highest modulus value, while C3 has the lowest modulus value. Among aramid-reinforced composites, the

Table 4

TENSILE TEST RESULTS OF SAMPLES					
Sample code	Strain range is taken into account in calculations		Tensile modulus, E (GPa)	Tensile strength (MPa)	Poisson's ratio, ν
	ε_{min} (-)	ε_{max} (-)			
C1	0.00300	0.00594	4.17	70	0.223
C2	0.00378	0.00822	9.42	290	0.875
C3	0.00276	0.00651	0.30	3.5	1.217
C4	0.00157	0.00428	28.95	130	0.075
C5	0.00193	0.00611	29.14	220	–0.05
C6	0.00085	0.00595	28.51	215	–0.015

modulus value of C4 is 7 times higher than C1 and 3 times higher than C2. C5 has a modulus 1.2 times greater than C6 when UHMWPE composites are evaluated among themselves. The tensile strength of Artec reinforced composite, which shows the highest tensile strength among aramid-reinforced composites, is 1.4 times higher than that of Dyneema H62 reinforced composite, which shows the highest tensile strength among UHMWPE UD-reinforced composites. However, when compared in modulus value, UHMWPE UD Dyneema H62 reinforced composite is 3.1 times more than Aramid woven Artec composite.

First, we evaluated the optical data recorded during the tests using the Vic3D software. Then, we calculated the stress values from the force values and matched them precisely with the strain values. Figure 5 presents the strain distributions obtained from the Vic3D software. The interlocking of warp and weft in C2 (290 MPa), which showed the highest tensile strength value, transfers the load to more than one yarn when examining the strain distribution in the tensile direction (ε_{yy}). When subjected to a load, these yarns contribute as a whole and absorb more energy before breaking. As shown in previous studies [6], the hybrid composite panel made of woven C1 and C2 reinforcements is better at absorbing energy than the others. It was observed that the load distribution of the C3 sample was not homogeneous, and as a result, the tensile strength value was at its lowest value compared to other samples.

Poisson's ratios-strain curves of composite samples are given in figure 6. The tensile test of the composites revealed different tendencies in the change of Poisson's ratios. Poisson's ratio is lowest in C6 and highest in C3. The order of Poisson's ratios is C5<C6<C4<C1<C2<C3. The increase in tensile strain caused a positive Poisson's ratio response in the C1, C2, and C3 samples. However, it caused a

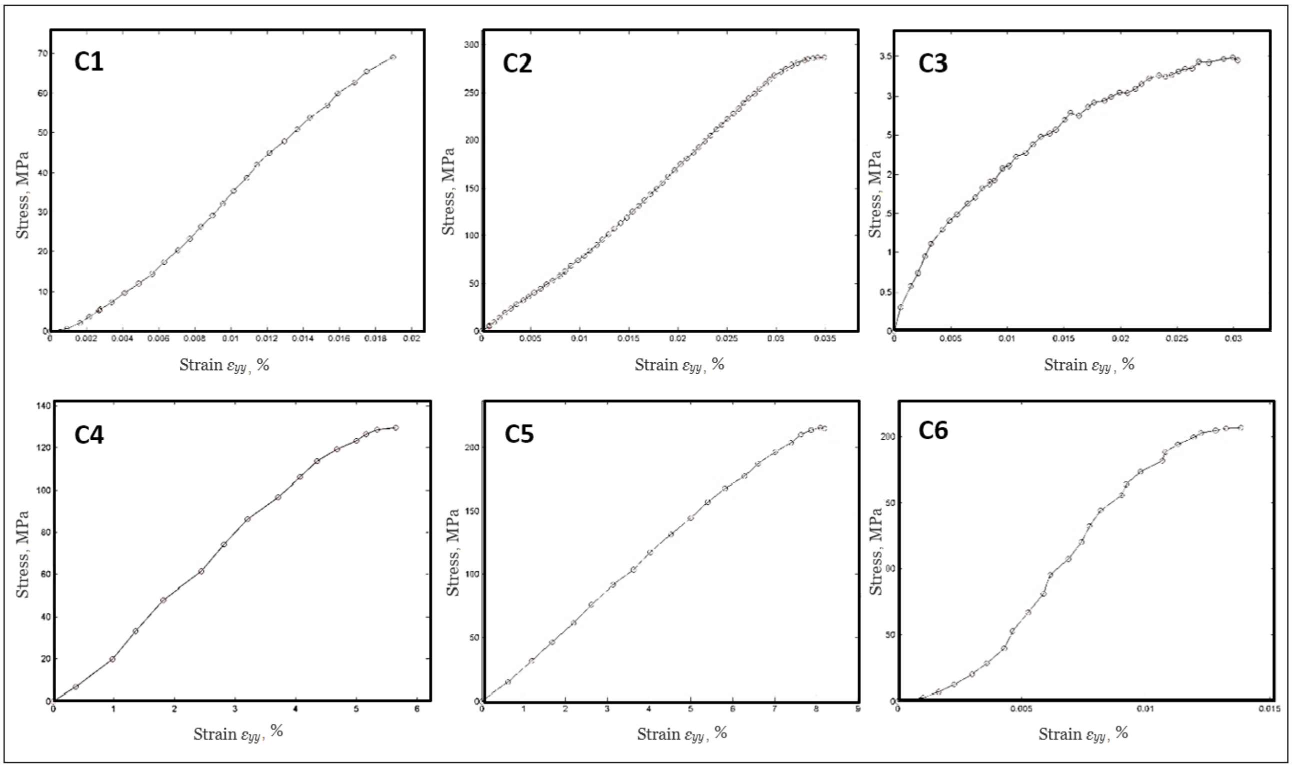

Fig. 4. Tensile stress versus strain curves of composites

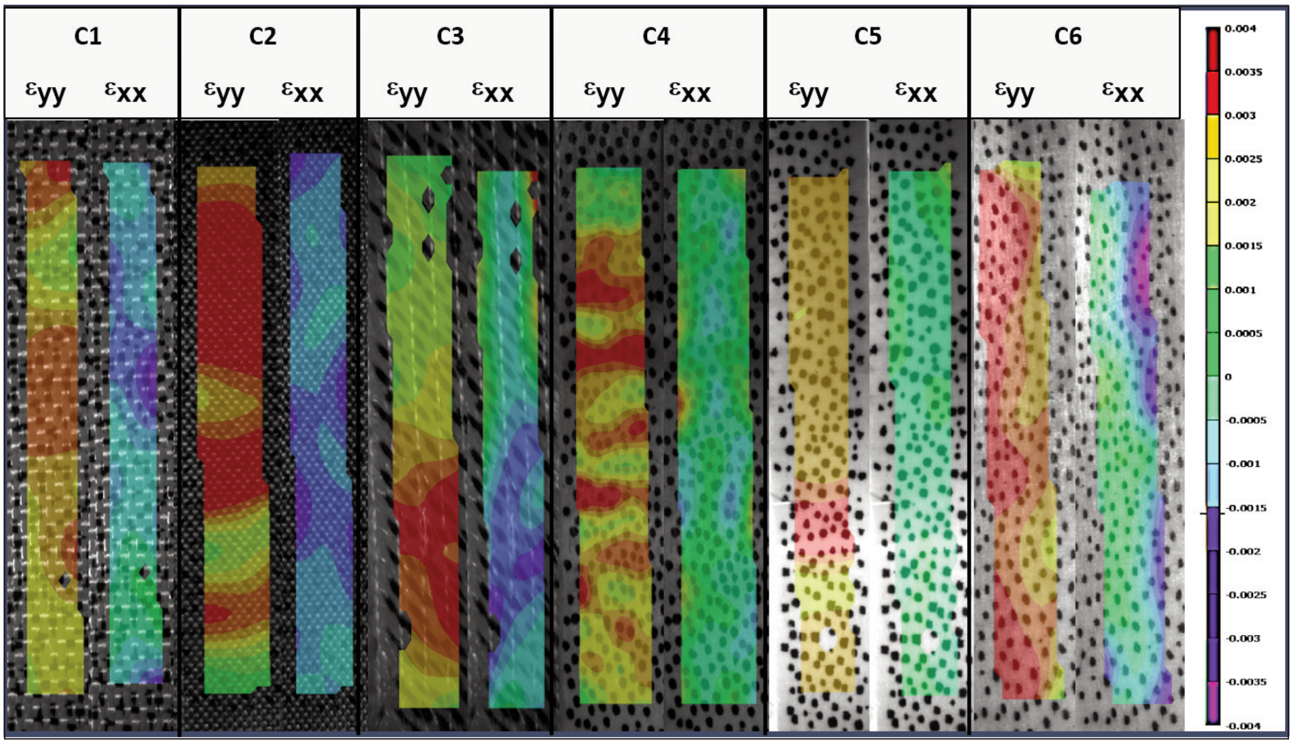

Fig. 5. Strain distributions of composite (ε_{yy} ≈ % 3)

negative Poisson's ratio (auxetic structures) response in C4, C5, and C6 samples. In this way, these samples expand as the tensile stress increases. It was seen that the C4, C5, and C6 samples grew in the *x* direction or lateral direction, even though a tensile force was being applied in the *y* direction when the strain distributions shown in figure 5 were looked at. It is observed that the Poisson's ratio decreases as the strain value increases in the C4 and C5 samples, but this decrease is unstable in the C4 sample. However, the C6 sample had the lowest Poisson ratio value at a strain of 7%. It was observed that this value progressed in a positive direction as the compression ratio increased, and this increase was observed to be faster after a tension value of 20%. Thanks to these auxetic structures, the composite will perform more effectively by dissipating or absorbing energy. In addition, in the C3 (Aramid Bi-Axial Non-Crimp) sample, the Poisson's ratio is relatively higher than in other samples due to the fibre arrangement of the fabrics being 45°/–45°. Figure 5 shows an apparent narrowing in the lateral direction when the sample is exposed to load in the tensile direction. Therefore, it will not be possible to distribute the load when exposed to impact, so its energy absorption performance will be quite low. This subject will be discussed in detail in the following sections (figure 6).

The tensile strength, modulus, and Poisson's ratio values of the samples are compared among themselves in table 4 and figure 7. Changes in fabric properties highly affect the performance of the reinforcement. This can be attributed to the difference in the reinforcement material's areal density, tensile strength, and architecture. The fabric structure and mechanical properties of the fibre caused these differences. In this context, although the C2 composite consists of woven fabric, its tensile strength is 4.1 times higher than C1 and 2.2 times higher than C4, thanks to the thin yarn (58/58 Tex) that causes the crimp to be low. It is known that a lower crimp results in higher mechanical properties [5, 30, 31].

The C1 sample had a much higher tensile strength value compared to the C3 sample, despite both samples being produced from the same yarn and having approximately equal unit area masses. There was non-crimp in the yarn in the C3 sample, so it was expected to have better mechanical properties than the C1 sample [5]. However, the results show that the maximum force value of sample C3 is lower than sample C1, which consists of woven fabric. The deformation of the filament by the needle due to friction between the needle and yarn during the production of biaxial fabric can explain this paradox. In addition, all tests were carried out in the 0 direction, whereas in the C3 (Aramid Bi-Axial Non-Crimp) sample, the fibre alignment of the fabrics was 45°/–45°. Due to this, the tensile strength value was very low, as the fibres could not fully carry the load. Other researchers have also reported this situation [32, 33]. C4 has 86% higher tensile strength compared to C1. The R4 fabric used to reinforce composite panel C4 exhibits a higher areal density, a larger tensile modulus, and a unidirectional structure. In contrast, the R1 fabric used in the C1 composite panel is woven with a basket weave with 0.8% crimp. The undesirable effect of this bending is excessive bending of the panel during loading, which causes the panel to have a lower tensile value. The thicker yarn linear density

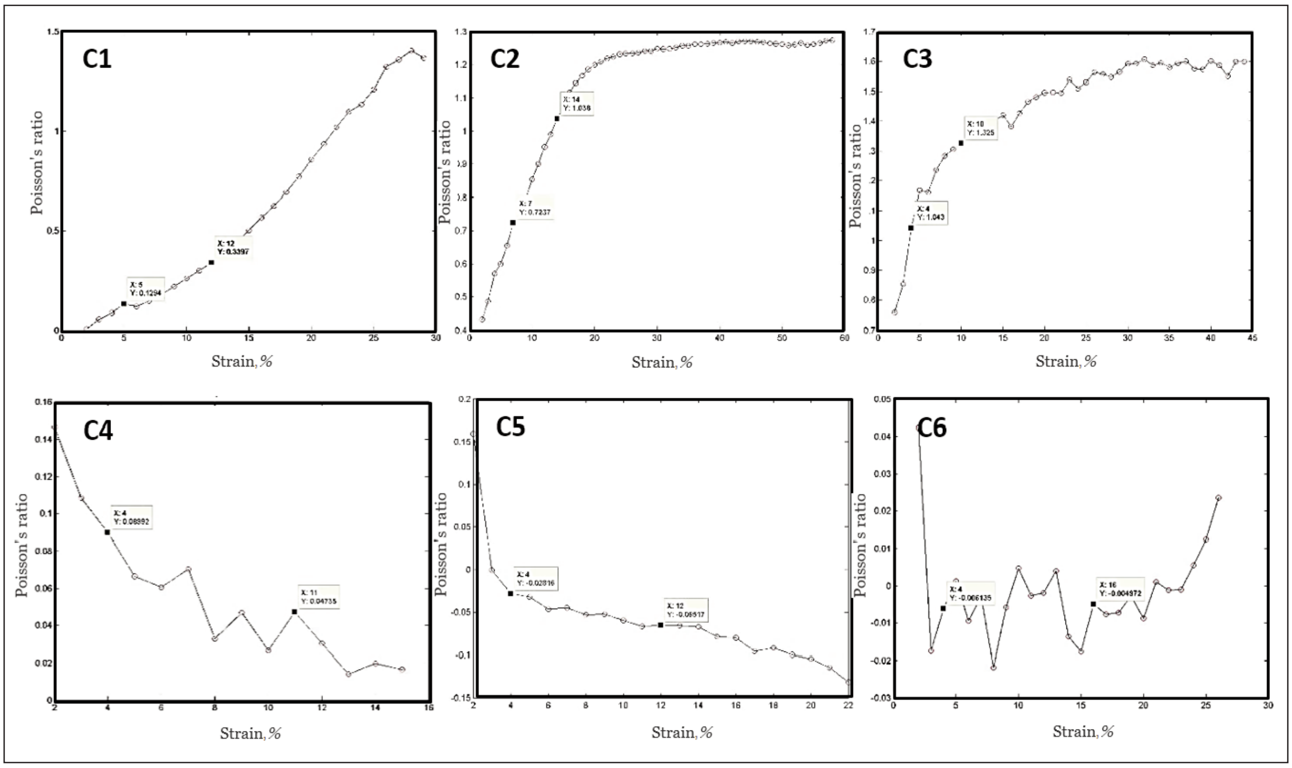

Fig. 6. Poisson's ratio of composites

(336 Tex) in reinforcement R1 contributes to the lower tensile strength value. Thin yarn offers more surface area and can carry more load than thick yarn. The stress-strain values of composite panel C4 reinforced with fabric R4 (non-crimp and thin yarn linear density) show that this effect is real.

C5 and C6 composites produced from UHMWPE H62 and H5T sheets show similar tensile strength values, respectively. The architecture area and yarn linear density of the reinforcement fabrics used for C5 and C6 panels are the same. C5 and C6 composite are lighter than others (C1, C3, and C4). Lighter plates resulted in better stress-strain values.

Ballistic armour resists penetration by bullets through the dissipation of impact energy. Critical features in ballistic armour design include hardness, strength, and toughness. A low Poisson ratio indicates that a material does not undergo much lateral expansion when subjected to axial deformation. This property affects the way the material distributes and absorbs impact energy. In this case, in table 4 and figure 7, the C5 and C6 composite panels made by strengthening the UD layer of UHMWPE Dyneema H62 and H5T have the lowest Poisson's ratio values, which are about –0.05. This negative Poisson's ratio (Auxetic) indicates that the material expands in the lateral direction when axial force is applied. This lateral expansion increases the composites' energy absorption and impact resistance, effectively reducing ballistic and explosive damage. Among the plates reinforced with Aramid fabrics, the one with the lowest Poisson ratio is the C4 composite reinforced with Aramid UD GS3000 fabric. Since the fibres of UD fabrics are aligned in one direction, deformation occurs more quickly. Aligning the fibres in one direction reduces the tendency to expand in the other direction when tension is applied. The high modulus, low density, and negative Poisson's ratio of C4, C5,

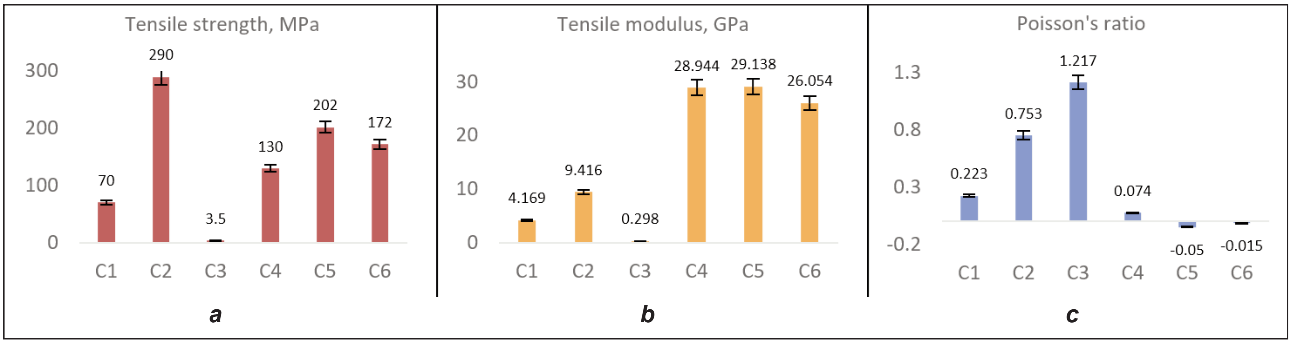

Fig. 7. Tensile test results of composite panels: *a* – Tensile strength; *b* – Tensile modulus; *c* – Poisson's ratio

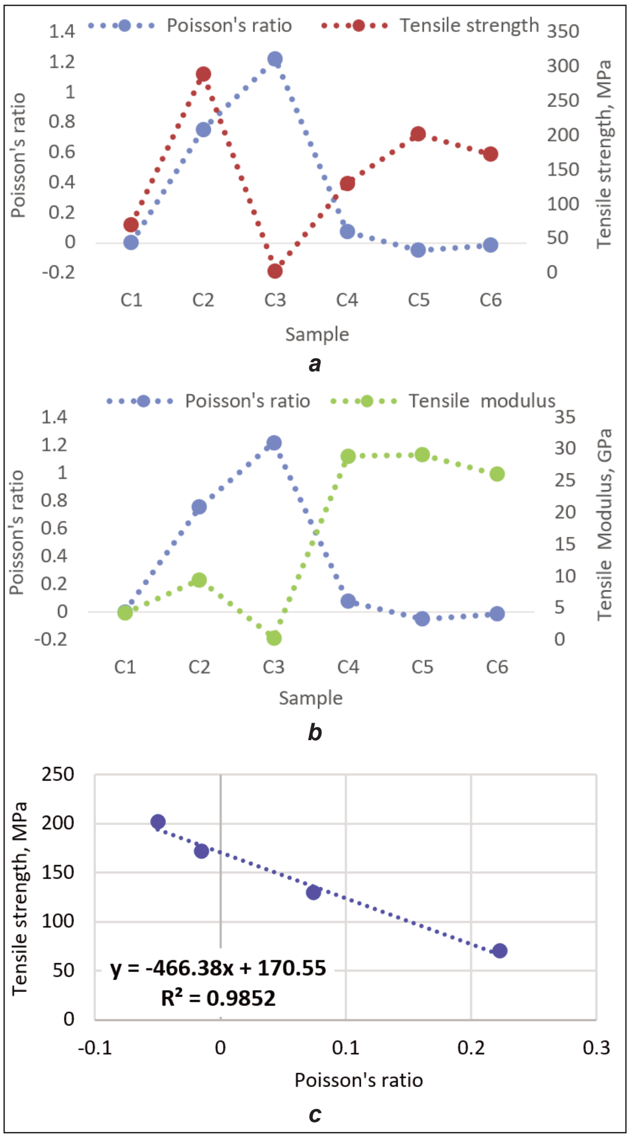

Fig. 8. Poisson's ratio versus: *a* – Tensile stress; *b* – Modulus of composites; *c* – Pearson correlation coefficient between Poisson's Ratio and tensile strength

and C6 composite panels with non-crimp UD fabrics can quickly disperse the strain wave away from the impact point.

Figure 8 depicts the relation of Poisson’s ratio with tensile strength and modulus. It was concluded that Poisson’s ratio has an inverse relation with tensile strength and modulus.

Relationship between elastic properties and energy absorption properties under low-velocity impact

Researchers examined the energy absorption behaviour of composites under low-speed impact in a previous study [6] using the same samples. Figure 9 illustrates the relationship between the energy absorption results obtained under low-velocity impact and the Poisson ratio results obtained in this study.

When table 5 is examined, the best results of energy absorption performance were obtained from C1 and C4 samples. There was no significant difference between the energy absorption performances of these two. The C3 sample exhibited the lowest energy absorption performance.

Table 5

IMPACT TEST RESULTS OF SAMPLES AT 1680 J ENERGY LEVEL [6]

Sample code	Absorbed energy (%)	Absorbed energy (J)
C1	91.8	1469±67
C2	86.8	1388±42
C3	76.3	1222±210
C4	91.7	1467±58
C5	87.9	1406±33

Figure 9 shows that the energy absorption performance under low-impact strain is related to Poisson's ratio. The lateral expansion tendency of C1, C4, and C5, as evident in the strain distributions (figure 5) and Poisson's ratio-strain curves (figure 6), significantly increased the energy absorption performance of

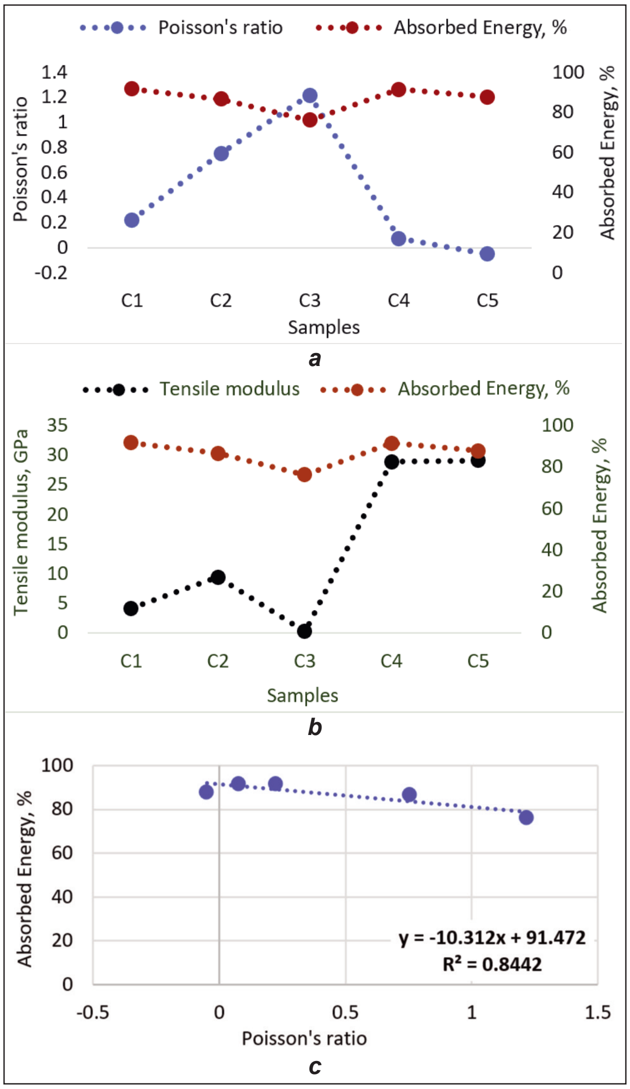

Fig. 9. Relationship between: *a* – Poisson's ratio-absorbed energy and *b* – Tensile modulus-absorbed energy; *c* – Pearson correlation coefficient between Poisson's Ratio and absorption energy under low-velocity impact (absorbed energy values taken from [6])

these samples. The C3 sample with the highest Poisson ratio showed the lowest energy absorption performance. In addition, although the C1 sample is higher than C4 and C5, its energy absorption performance is close. This phenomenon can be attributed to the architecture and area density of the reinforcement fabric of sample C1. However, as shown in figure 6, C1 showed Poisson's ratio values of 0 at low strain ratios (1–4%), and as a result, it showed energy absorption performance similar to C4 and C5 under low-velocity impact. When figure 9, *b* is examined, the modulus value of the C4 and C5 samples is the highest. A high modulus increases the deformation resistance of the material under tension, thus absorbing energy. C4 and C5 have the highest energy absorption performance, in line with their high modulus values.

Relationship between elastic properties and energy absorption properties under dynamic compressive loading

In a previous study [27] with the same samples, the composites' high strain rate compression properties and their energy absorption behaviour under the Split Hopkinson Pressure Bar (SHPB) 8 bar pressure test at room temperature were examined. Figure 10 shows the relationship between the energy absorption results obtained under high-speed impact and the Poisson's ratio results obtained in this study.

In the relevant study [27], dynamic compressive loading tests of composites reinforced with woven and UD fabrics made of aramid and UHMWPE were performed. The strain rate was changed in the tests by changing the bullet shot pressure. The pressure bar value was selected as 8 bar. The energy absorption behaviour of eight types of samples was noted.

The energy absorption performance of C1, C4, C5 and C6 composite panels under the split Hopkinson 8 bar pressure test is shown in table 6. The C5 sample showed the best energy absorption performance, and C1 showed the worst. It was observed that the absorption energies of C5 and C6 were very close.

Composites reinforced with a high auxetic structure showed higher impact energy absorption performance than composites reinforced with a lower auxetic structure. Figure 10 shows the absorbed energy results of the Poisson's ratio of the structure and the corresponding composites. The absorbed energy of the corresponding composites had a direct relationship with the negative Poisson's ratio of the samples.

Table 6

ABSORBED ENERGY VALUES OF THE COMPOSITE SAMPLES FOR 8 BAR (ABSORBED ENERGY VALUES TAKEN FROM [27])	
Sample code	**Absorbed energy (J/mm^3)**
C1	47.78
C4	49.15
C5	60.86
C6	57.36

This finding suggests that reinforcement fabrics with a lower Poisson's ratio have a greater capacity to couple and resist the applied force at the point of impact, resulting in increased energy absorption capacity. Figure 10 shows a direct relationship between the modulus and the energy absorption performance of the samples. The energy absorption performance of C4, C5, and C6 samples, which have approximately the same modulus values, is at very close values. The C1 sample with the lowest modulus value has the lowest energy absorption performance. The noteworthy point is that although the energy absorption performance of the C1 sample showed close values to C5 under the low-velocity impact test, it showed the lowest value in the dynamic compressive loading test. This showed that the stress gradually and moderately linearly increased with the applied strain. This is in line with what we found in the low-velocity impact testing study [6]: the composites behaved almost statically when strain rates were low. As shown in figure 6, while the

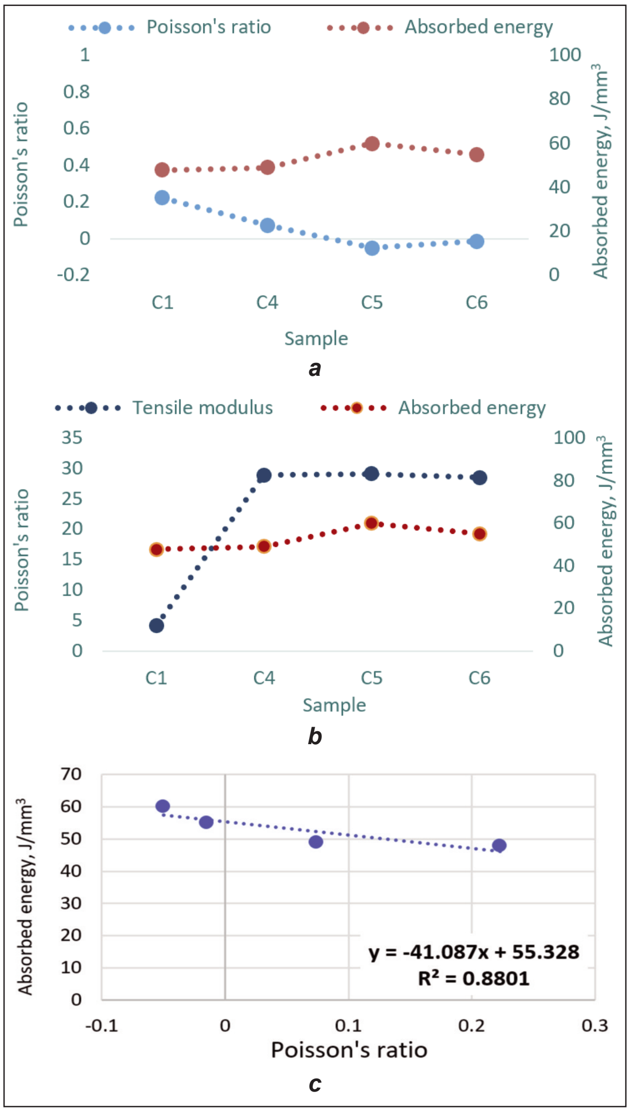

Fig. 10. Relationship between: *a* – Poisson's ratio and absorbed energy; *b* – Tensile modulus-absorbed energy; *c* – Pearson correlation coefficient between Poisson's Ratio and absorption energy under dynamic compressive loading (absorbed energy values taken from [27])

Poisson's ratio of C1 showed 0 values at low strain ratios, as the strain ratios increased, the Poisson's ratio rapidly increased positively. As a result, the energy absorption peak decreased. However, as the strain rate increased during the SHPB test, a noticeable improvement in material hardness and strength appeared, indicating the existence of strain rate sensitivity. This can be attributed to the inherent viscoelastic properties of thermoplastic composites, resulting in energy dissipation at high strain rates. The strain rate sensitivity observed in the SHPB test reveals the material's potential for energy-absorbing applications under impact and dynamic loading conditions. In addition, SHPB test data facilitated the calculation of the composites' dynamic modulus and damping properties and offered valuable information regarding their response to rapid deformation. These findings underscore the importance of considering strain rate effects when designing composites for high-speed applications.

Relationship between elastic properties and energy absorption properties under ballistic impact

In a previous study [8] with the same samples, the energy absorption performances of the composites under the ballistic impact V50 test were examined. Figure 11 shows the relationship between the energy absorption results obtained under ballistic impact and the Poisson's ratio results obtained in this study.

This part focuses on the analysis of composites composed of aramid and UHMWPE. The main focus of this research is on the evaluation of the impact behaviour of these composites. The effects of various factors, especially fibre type, fabric structure, and orientation of the fabric layer, have been investigated. Three different fabric structures were used to reinforce aramid composites, while two were used for UHMWPE composites. The researchers evaluated the ballistic performance by measuring energy absorption. The findings of the study revealed that UD composites exhibited superior ballistic performance in terms of energy absorption (Ea) per ballistic unit weight [8].

Table 7

CONTACT ANGLE MEASUREMENT RESULTS OF FABRICS

Sample code	*Ea* (J)	*Ea*/AD (Jm^2/kg)
C1	547	54
C3	536	56
C4	732	60
C5	569	70
C6	594	68

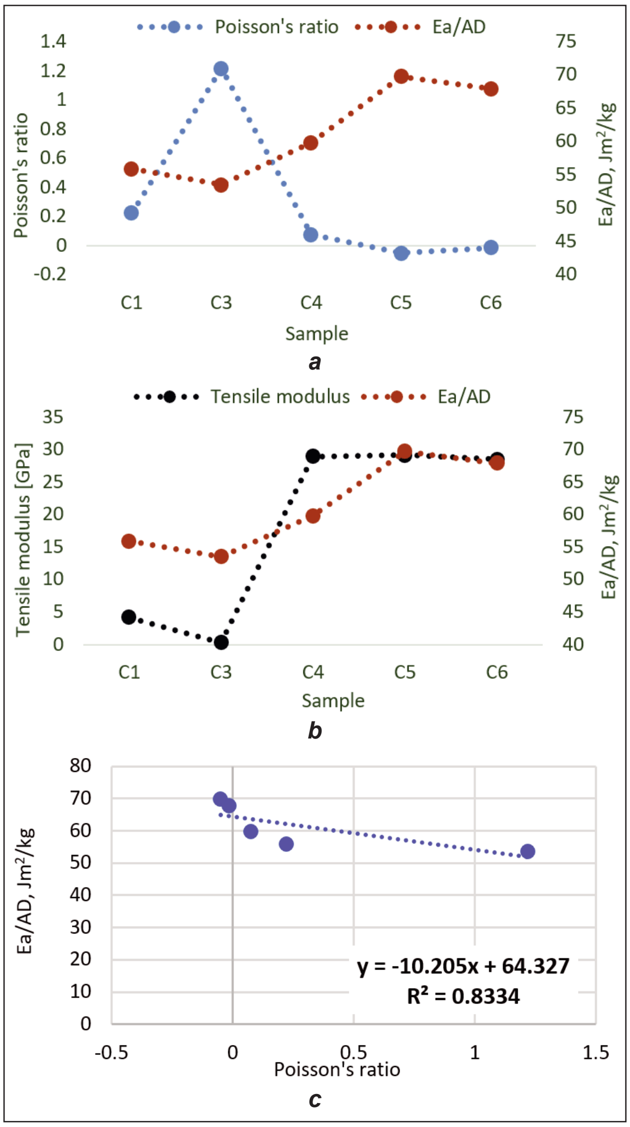

Fig. 11. Relationship between: *a* – Poisson's ratio and Ea/AD; *b* – Tensile modulus-Ea/AD; *c* – Pearson correlation coefficient between Poisson's Ratio and Ea/AD under ballistic impact (absorbed energy values taken from [8])

Table 7 presents the properties of composite panels of the same thickness (9.5 ± 0.6 mm) reinforced with different numbers of fabric layers. Because the areal density of all reinforcement fabrics differs, the density of all composites differs according to the number of fabric layers. Composites with a more significant area density exhibit higher energy absorption performance. The C4 composite panel reinforced with UD-aramid-GS3000 shows the highest Ea values due to the areal density. The C3 panel has 34.06% higher Ea than the aramid CT736 reinforced panel and 23.2% higher than the UHMWPE-H5T® sheet reinforced panel. However, UD-UHMWPE-H62® and UD-UHMWPE-H5T® reinforced composites showed better energy absorption per unit area density (Ea/AD). It would be more accurate to compare the Ea/AD of composites to see the effect of different material types on ballistic performance. The Ea/AD UD values of composites reinforced with UD-UHMWPE fabrics are higher than composites reinforced with woven aramid fabrics. The Ea/AD hierarchy of composites is as follows [8]:

Ea/AD C5 > C4 + C5 > C6 > C4 > C3 > C1

Figure 11 shows the variation of energy absorption per unit area density (Ea/AD) according to Poisson's ratio. In general, it has been observed that Poisson's ratio and Ea/AD are inversely related. Plates C3, C4, and C5 exhibited a negative Poisson's ratio. When axial force is applied to the material, it expands in the lateral direction. Their ability to expand under sudden dynamic forces has significantly increased the energy absorption capacity of the plates. These auxiliary materials, which expand when exposed to tension, have given new mechanical properties to C4, C5, and C6 plates. This increased tensile strength resulted in increased resistance to delamination. As a result, Aramid UD GS3000, UHMWPE UD Dyneema H62, and UHMWPE UD H5T UD reinforcement materials are highly effective for use in body armour systems where superior mechanical performance and dynamic impact resistance are critical. After applying impact force, structural changes account for the small changes in impact energy in UHMWPE UD Dyneema H62 and UHMWPE UD H5T reinforced composites. Figure 11 shows the change of Ea/AD according to the modulus value. As a result of the ballistic impact V50 test, the Ea/AD value showed the same characteristics as the modulus value. C5 and C6 samples with high modulus values showed the highest Ea/AD value. Sample C3, which has the lowest modulus value, showed the lowest Ea/AD value.

Relationship between elastic properties and energy absorption properties under low-velocity impact, dynamic compressive loading and ballistic impact

The energy absorption abilities per area density of Aramid woven fabric (CT 736), Aramid UD-GS3000, and UHMWPE UD-Dyneema H62 reinforcement fabrics were compared according to the results of our previous studies, low-velocity impact [6], split Hopkinson pressure bar [27], and ballistic impact V50 test [8] results.

In this context, the relationship between the energy absorption abilities of reinforcement fabrics per normalized area density and Poisson's ratio as a result of low-velocity impact testing, split Hopkinson pressure bar testing, and ballistic impact V50 testing is given in figure 12.

The split Hopkinson pressure bar test and the ballistic impact V50 tests at high speed showed that Aramid UD-GS3000 reinforced plates did better than CT-736 reinforced plates. The high impact energy of Aramid UD-GS3000 and UHMWPE UD-Dyneema H62 reinforced plates is because of the changes in their structure when the impact force is applied. These changes happen because of the high compression stress in split Hopkinson pressure bar tests and ballistic impact V50 tests. The force changes the thickness of the initial sample; the plates expand laterally; thus, the force dissipation capacity of the sample increases, and thus the energy absorption performance increases. The Poisson's ratio graphs of C4-C5 samples in figure 5 indicate this phenomenon. Aramid UD-GS3000 and UHMWPE UD-Dyneema H62 reinforcement fabrics act as auxiliary materials at high-impact stresses. The crimp-free yarns of these fabrics absorb impact loads efficiently and distribute the force throughout the structure. Higher filler yarn density increases energy absorption.

Interestingly, unlike other tests, Aramid woven fabric (CT 736 fabric) gave the best results in low-velocity impact testing. As seen from here, the energy absorption capacity decreases as the impact speed increases in CT 736-reinforced plates. Figure 6 shows that the Poisson's ratio of the Aramid woven fabric-CT 736 reinforced plate is close to 0 at low-impact strains. This caused this reinforcement fabric to show better energy absorption ability at low-impact velocities. Aramid UD-GS3000 and UHMWPE UD-Dyneema H62 reinforcement fabrics showed similar results in low-velocity impact testing, but UHMWPE UD-Dyneema H62 reinforcement fabric showed a slightly higher energy absorption performance. As stated in figure 6, this means that UHMWPE UD-Dyneema H62 has a slightly lower Poisson ratio than Aramid UD-GS3000 at low-impact strains, resulting in higher energy absorption performance.

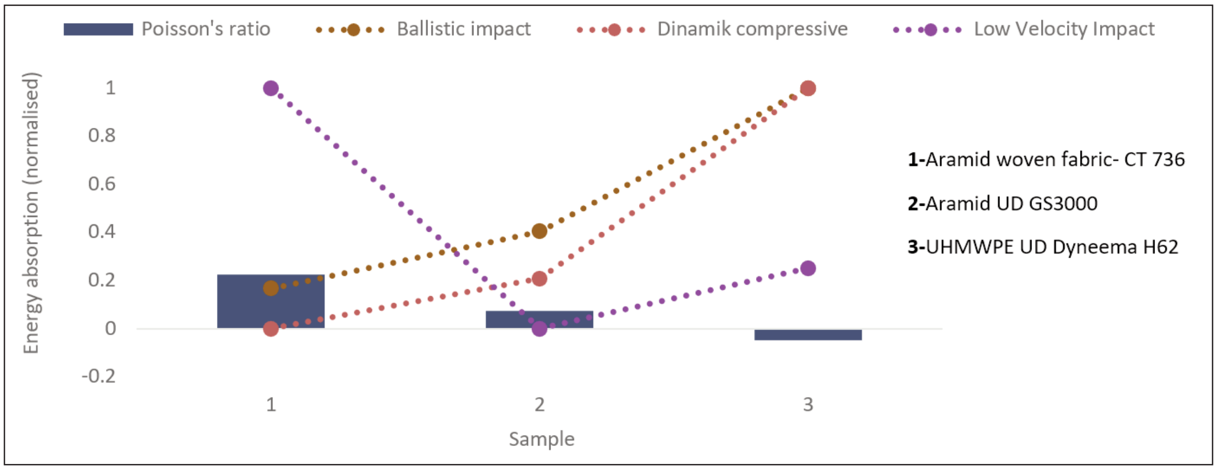

Fig. 12. The relationship between the energy absorption abilities (normalised) of reinforcement fabrics and Poisson's ratio

CONCLUSIONS

Within the scope of this study, the mechanical properties and strain distributions of composite materials produced from different aramid and ultra-high molecular weight polyethylene fabrics were examined. Then, these analysis results were analysed in detail about the energy absorption data obtained from our previous studies, including low-velocity impact, dynamic compressive, and ballistic impact V50 tests. Based on our results, the following conclusions are made:

- Although the tensile modulus values of unidirectional fabric-reinforced composites are very close, they have higher tensile modulus values than other woven and biaxial composites. The UHMWPE UD with the highest tensile modulus was obtained in the Dyneema H62 composite.
- The tensile strength value of Artec aramid-woven fabric-reinforced composite is higher than all other composites, thanks to the thin yarn (58/58 Tex). Among UHMWPE UD composites, the highest tensile strength value was obtained from Dyneema H62 sheet-reinforced composite. Artec aramid composite has 32% higher tensile strength than Dyneema H62 composite.
- Poisson's ratios of UHMWPE UD fabric-reinforced composites showed negative values. As a result of the strain distributions obtained from Vic3D software, it was seen that they behaved as an auxetic structure. The UD aramid-GS3000 fabric reinforced and Dyneema H62 composite exhibited a negative Poisson's ratio as the tensile value increased. In contrast, the UHMWPE H5T composite displayed an unstable structure with a positive Poisson's ratio after reaching the 20% tensile value.
- Among aramid fabric-reinforced composites, the lowest Poisson ratio is UD aramid-GS3000 fabric-reinforced composite and is approximately 0. Additionally, as the stress value increased, the Poisson's ratio moved negatively. However, the Aramid woven fabric-CT 736 woven reinforced composite was close to 0 at a low-tension value and showed a rapid positive increase as this tension value increased.
- A linear relationship was observed between energy absorption performance, Poisson's ratio, and tensile modulus.
- In dynamic compressive and ballistic impact V50 tests, the UHMWPE UD composites absorb energy the best, with Poisson's negative ratio. The UD aramid-GS3000 composite has the lowest Poisson ratio of all the aramid composites. The energy absorption of UHMWPE UD composite is 27% higher than that of Aramid woven fabric-CT 736 composite. However, in the low-velocity impact test, Aramid woven fabric-CT 736 composites showed the highest absorption performance. It has been observed that this situation is directly due to Poisson's ratio showing 0 values at the low-tension value of the Aramid woven fabric-CT 736 composite.

According to these findings, it has been determined that Poisson's ratio, tensile modulus, architecture, and areal density of the reinforcement materials are the main factors affecting the energy absorption performance of composites. Composites with high modulus, negative Poisson's ratio, low density, and non-curling UD fabrics have the highest energy absorption performance. It was concluded that these parameters should be analysed in detail in selecting reinforcement materials for composites to be used in ballistic protection applications.

REFERENCES

[1] Karahan, M., Karahan, E.A., *Development of an innovative sandwich composite material for the protection of lower limb against landmine explosion: mechanical leg test results*, In: Text Res J, 2016, 87, 15–30, https://doi.org/10.1177/0040517515624880

[2] Karahan, M., Karahan, N., *Development of an innovative sandwich composites for the protection of lower limbs against landmine explosions*, In: J Reinf Plast Compos, 2016, 35, 1776–1791, https://doi.org/10.1177/0731684416668261

[3] Karahan, M., Kuş, A., Eren, R., *An investigation into ballistic performance and energy absorption capabilities of woven aramid fabrics*, In: Int J Impact Eng, 2008, 35, 499–510, https://doi.org/10.1016/J.IJIMPENG.2007.04.003

[4] Karahan, M., Karahan, N., Nasir, M.A., Nawab, Y., *Effect of structural hybridization on ballistic performance of aramid fabrics*, In: J Thermoplast Compos Mater, 2018, 32, 795–814, https://doi.org/10.1177/0892705718780197

[5] Karahan, M., *Comparison of Ballistic Performance and Energy Absorption Capabilities of Woven and Unidirectional Aramid Fabrics*, In: Text Res J, 2008, 78, 718–730, https://doi.org/10.1177/0040517508090487

[6] Karahan, M., Yildirim, K., *Low velocity impact behaviour of aramid and UHMWPE composites*, In: Fibres Text East Eur, 2015, 23, 97–105, https://doi.org/10.5604/12303666.1152522

[7] Khan, M.I., Umair, M., Hussain, R., Karahan, M., Nawab, Y., *Investigation of impact properties of para-aramid composites made with a thermoplastic-thermoset blend,* In: J Thermoplast Compos Mater, 2021, 36, 866, https://doi.org/10.1177/08927057211021464

[8] Karahan, M., Jabbar, A., Karahan, N., *Ballistic impact behavior of the aramid and ultra-high molecular weight polyethylene composites*, In: J Reinf Plast Compos, 2015, 34, 37–48, https://doi.org/10.1177/0731684414562223

[9] Ari, A., Karahan, M., Kopar, M., Ahrari, M., T*he effect of manufacturing parameters on various composite plates under ballistic impact*, In: Polym Polym Compos, 2022, 30, 1–15, https://doi.org/10.1177/09673911221144874

[10] Zhou, W., Wente, T., Liu, D., Mao, X., Zeng, D., Torab, H., et al., *A comparative study of a quasi 3D woven composite with UD and 2D woven laminates*, In: Compos Part A Appl Sci Manuf, 2020, 139, 106139, https://doi.org/10.1016/J.COMPOSITESA.2020.106139

[11] Bao, J. wei, Wang, Y. wei, An, R., Cheng, H. wu, Wang, F. chi, *Investigation of the mechanical and ballistic properties of hybrid carbon/ aramid woven laminates*, In: Def Technol, 2022, 18, 1822–1833, https://doi.org/10.1016/J.DT.2021.09.009

[12] Tam, T., Bhatnagar, A., *High-performance ballistic fibres and tapes*, In: Ashok Bhatnagar, editor. Light. Ballist. Compos. Mil. Law-Enforcement Appl. Second Ed. Second Edi, Woodhead Publishing, 2016, 1–39, https://doi.org/10.1016/B978-0-08-100406-7.00001-5

[13] Barhoumi, H., Bhouri, N., Feki, I., Baffoun, A., Hamdaoui, M., Ben Abdessalem, S., *Review of ballistic protection materials: Properties and performances*, In: J Reinf Plast Compos, 2022, 42, 685–699, https://doi.org/10.1177/07316844221137920

[14] Bajya, M., Majumdar, A., Butola, B.S., Arora, S., Bhattacharjee, D., *Ballistic performance and failure modes of woven and unidirectional fabric based soft armour panels*, In: Compos Struct, 2021, 255, 112941, https://doi.org/10.1016/J.COMPSTRUCT.2020.112941

[15] Zhou, G., Sun, Q., Meng, Z., Li, D., Peng, Y., Zeng, D., et al., *Experimental investigation on the effects of fabric architectures on mechanical and damage behaviors of carbon/epoxy woven composites*, In: Compos Struct, 2021, 257, 113366, https://doi.org/10.1016/J.COMPSTRUCT.2020.113366

[16] Lopresto, V., Leone, C., De Iorio, I., *Mechanical characterisation of basalt fibre reinforced plastic*, In: Compos Part B Eng, 2011, 42, 717–723, https://doi.org/10.1016/J.COMPOSITESB.2011.01.030

[17] Ullah, T., Hussain, M., Ali, M., Umair, M., *Impact performance of jute 3D woven auxetic reinforced thermoplastic (PC/PVB) composites*, In: J Reinf Plast Compos, 2023, https://doi.org/10.1177/07316844231171707

[18] Erdoğan, İ., Toktaş, İ., *Investigation of the Auxetic of a novel geometric structure and improvement of Poisson's ratio at different inner thicknesses*, In: Gazi Üniversitesi Fen Bilim Derg Part C Tasarım ve Teknol, 2023, https://doi.org/10.29109/gujsc.1346281

[19] Ullah, T., Hussain, M., Ali, M., Umair, M., *Impact of auxeticity on mechanical properties of 3D woven auxetic reinforced thermoplastic composites*, In: Polym Compos, 2023, 44, 897–906, https://doi.org/10.1002/pc.27141

[20] Nguyễn, H., Fangueiro, R., Ferreira, F., Nguyễn, Q., A*uxetic materials and structures for potential defense applications: An overview and recent developments*, In: Text Res J, 2023, 93, 5268–5306, https://doi.org/10.1177/00405175231193433

[21] Li, T., Liu, F., Wang, L., *Enhancing indentation and impact resistance in auxetic composite materials*, In: Compos Part B Eng, 2020, 198, 108229, https://doi.org/10.1016/J.COMPOSITESB.2020.108229

[22] Zhou, L., Zeng, J., Jiang, L., Hu, H., L*ow-velocity impact properties of 3D auxetic textile composite*, In: J Mater Sci, 2018, 53, 3899–3914, https://doi.org/10.1007/S10853-017-1789-8

[23] Ahmed, H.I., Umair, M., Nawab, Y., Hamdani, S.T.A., *Development of 3D auxetic structures using para-aramid and ultra-high molecular weight polyethylene yarns*, In: J Text Inst, 2021, 112, 1417–1427, https://doi.org/10.1080/00405000.2020.1819007

[24] Evans, K.E., Alderson, K.L., *Auxetic materials: the positive side of being negative*, In: Eng Sci Educ J, 2000, 9, 148–154, https://doi.org/10.1049/ESEJ:20000402

[25] Steffens, F., Rana, S., Fangueiro, R., *Development of novel auxetic textile structures using high performance fibres*, In: Mater Des, 2016, 106, 81–89, https://doi.org/10.1016/j.matdes.2016.05.063

[26] Liaqat, M., Samad, H.A., Hamdani, S.T.A., Nawab, Y., *The development of novel auxetic woven structure for impact applications*, In: J Text Inst, 2017, 108, 1264–1270, https://doi.org/10.1080/00405000.2016.1239330

[27] Shaker, K., Jabbar, A., Karahan, M., Karahan, N., Nawab, Y., *Study of dynamic compressive behaviour of aramid and ultrahigh molecular weight polyethylene composites using Split Hopkinson Pressure Bar,* In: J Compos Mater, 2017, 51, 81–94, https://doi.org/10.1177/0021998316635241

[28] Karahan, M., Jabbar, A., Karahan, N., *Ballistic impact behavior of the aramid and ultra-high molecular weight polyethylene composites*, In: J Reinf Plast Compos, 2014, 34, 37–48, https://doi.org/10.1177/0731684414562223

[29] Zee, R.H., Hsieh, C.Y., *Energy absorption processes in fibrous composites*, In: Mater Sci Eng A, 1998, 246, 161–168, https://doi.org/10.1016/S0921-5093(97)00735-1

[30] Karahan, M., Ulcay, Y., Eren, R., Karahan, N., Kaynak, G., *Investigation into the Tensile Properties of Stitched and Unstitched Woven Aramid/Vinyl Ester Composites*, In: Text Res J, 2009, 80, 880–891, https://doi.org/10.1177/0040517509346441

[31] Karahan, M., Ulcay, Y., Karahan, N., Kuş, A., *Influence of stitching parameters on tensile strength of aramid/vinyl ester composites*, In: Medziagotyra, 2013, 19, 67–72, https://doi.org/10.5755/J01.MS.19.1.3829

[32] Mittal, R.K., Jafri, M.S., *Influence of fibre content and impactor parameters on transverse impact response of uniaxially reinforced composite plates*, In: Composites, 1995, 26, 877–886, https://doi.org/10.1016/0010-4361(95)90881-Y

[33] Zhu, X., Chen, W., Liu, L., Xu, K., Luo, G., Zhao, Z., *Experimental investigation on high-velocity impact damage and compression after impact behavior of 2D and 3D textile composites*, In: Compos Struct, 2023, 303, 116256, https://doi.org/10.1016/J.COMPSTRUCT.2022.116256

Authors:

ALİ ARI[1], MEHMET KARAHAN[2,3]

[1]Department of Weapon Industry Technician, Vocational School of Higher Education, Ostim Technical University,
06374, Ankara, Türkiye

[2]Vocational School of Technical Sciences, Bursa Uludag University, 16059, Bursa, Türkiye
e-mail: mkarahan@uludag.edu.tr

[3]Butekom Inc., Demirtas Dumlupinar OSB District, 2nd Cigdem Street No:1/4, 16245, Osmangazi, Bursa, Türkiye

Corresponding author:

ALİ ARI
e-mail: ali.ari@ostimteknik.edu.tr