TEKSTİL VE MÜHENDİS

(Journal of Textiles and Engineer)

http://www.tekstilvemuhendis.org.tr

LINEAR DENSITY CHRONICLES: INVESTIGATING THE IMPACT OF E-GLASS THERMOSET AND THERMOPLASTIC COMPOSITES

DOĞRUSAL YOĞUNLUK KRONİKLERİ: TERMOSET VE TERMOPLASTİK E-CAM KOMPOZİTLERE ETKİSİNİN ARAŞTIRILMASI

Arvind VASHISHTHA[1]
Soumya CHOWDHURY[*2]
Dhirendra SHARMA[1]
Bijoy Kumar BEHERA[2]

[1]Department of Textile Technology, MLV Textile & Engineering College, Bhilwara (Raj.) India
[2]Department of Textile and Fibre Engineering, Indian Institute of Technology Delhi, India

Bu makaleye atıf yapmak için (To cite this article):

Arvind VASHISHTHA, Soumya CHOWDHURY, Dhirendra SHARMA, Bijoy Kumar BEHERA (2024): LINEAR DENSITY CHRONICLES: INVESTIGATING THE IMPACT OF E-GLASS THERMOSET AND THERMOPLASTIC COMPOSITES, Tekstil ve Mühendis, 31: 136, 211- 222.

For online version of the article: https://doi.org/10.7216/teksmuh.1461360

TMMOB Tekstil Mühendisleri Odası
UCTEA Chamber of Textile Engineers
Tekstil ve Mühendis
Journal of Textiles and Engineer

Yıl (Year) : 2024/4
Cilt (Vol) : 31
Sayı (No) : 136

Araştırma Makalesi / Research Article

LINEAR DENSITY CHRONICLES: INVESTIGATING THE IMPACT OF E-GLASS THERMOSET AND THERMOPLASTIC COMPOSITES

Arvind VASHISHTHA[1]
Soumya CHOWDHURY*[2]
Dhirendra SHARMA[1]
Bijoy Kumar BEHERA[2]
[1]Department of Textile Technology, MLV Textile & Engineering College, Bhilwara (Raj.) India
[2]Department of Textile and Fibre Engineering, Indian Institute of Technology Delhi, India

Gönderilme Tarihi / Received: 01.04.2024
Kabul Tarihi / Accepted: 14.12.2024

ABSTRACT: This comprehensive investigation delves into the mechanical characteristics of E-glass reinforcement at varying linear densities in two-dimensional (2D) woven fabric-reinforced composites employing both thermoplastic and thermoset matrices. By scrutinizing tensile strength, flexural strength, edge-wise impact resistance and out-of-plane impact properties, the study optimizes composite materials and sheds light on the influence of linear density on the mechanical properties of thermoset and thermoplastic composites. Key insights underscore the superior in-plane load-bearing capacity of thermoset composites under quasi-static conditions, contrasting with the exceptional edge-wise and out-of-plane impact resistance exhibited by thermoplastic composites. Furthermore, the study reveals that thermoset composites outperform their thermoplastic counterparts in tensile and flexural properties, with discernible deviations in quasi-static mechanical properties with increasing linear density. In both thermoplastic and thermoset composites, specimens that had lower linear density reinforcement demonstrated enhanced mechanical performance under quasi-static circumstances. Nevertheless, when subjected to dynamic conditions, thermoplastic composites exhibited this pattern, whereas thermoset composites demonstrated divergent characteristics. In the context of low-velocity impact events, it was shown that Thermoplastic 600 Tex Glass Fabric Reinforced Composite (TP6G2DFRC) exhibited greater performance compared to all other specimens, even those with higher linear density. Conversely, in thermoset composites, Thermoplastic 1200 Tex Glass Fabric Reinforced Composite (TS12G2DFRC) demonstrated notable superiority over Thermoplastic 600 Tex Glass Fabric Reinforced Composite (TS6G2DFRC), despite possessing a higher linear density.

Keywords: Thermoplastic, thermoset, composites, E-glass, liner density

DOĞRUSAL YOĞUNLUK KRONİKLERİ: TERMOSET VE TERMOPLASTİK E-CAM KOMPOZİTLERE ETKİSİNİN ARAŞTIRILMASI

ÖZ: Hem termoplastik hem de termoset matrisleri kullanan iki boyutlu (2D) dokuma kumaş ile güçlendirilmiş kompozitlerde değişen doğrusal yoğunluklarda E-cam takviyesinin mekanik özelliklerini bu çalışma kapsamında araştırılmıştır. Çalışma, çekme mukavemetini, eğilme mukavemetini, darbe direncini ve düzlem dışı darbe özelliklerini inceleyerek kompozit malzemeleri optimize ediyor; yoğunluğun termoset ve termoplastik kompozitlerin mekanik özellikleri üzerindeki etkisine ışık tutuyor. Termoplastik kompozitlerin sergilediği olağanüstü darbe direncine yansıra termoset kompozitlerin üstün düzlem içi yük taşıma kapasitesi ortaya çıkmaktadır. Ayrıca çalışma, termoset kompozitlerin, artan doğrusal yoğunlukla birlikte yarı statik mekanik özelliklerde fark edilebilir sapmalar ile birlikte, çekme ve eğilme özelliklerinde termoplastik muadillerinden daha iyi performans gösterdiğini ortaya koymaktadır. Hem termoplastik hem de termoset kompozitlerde, daha düşük doğrusal yoğunluklu takviyeye sahip numuneler, yarı statik koşullar altında gelişmiş mekanik performans sergilemiştir. Bununla birlikte, dinamik koşullara maruz kaldığında termoplastik kompozitler bu modeli sergilerken, termoset kompozitler farklı özellikler sergilemiştir. Düşük hızlı darbe yüklemelerinde, Termoplastik 600 Tex Cam Kumaş Takviyeli Kompozitin (TP6G2DFRC) diğer tüm numunelerle, hatta daha yüksek doğrusal yoğunluğa sahip olanlarla karşılaştırıldığında daha yüksek performans sergilediği tespit edilmiştir. Termoplastik 1200 Tex Cam Kumaş Takviyeli Kompozit (TS12G2DFRC), daha yüksek doğrusal yoğunluğa sahip olmasına rağmen Termoplastik 600 Tex Cam Kumaş Takviyeli Kompozite (TS6G2DFRC) göre kayda değer bir üstünlük göstermiştir.

Anahtar Kelimeler: Termoplastik, termoset, kompozit, E-glass, yoğunluk

---

***Sorumlu Yazarlar/Corresponding Authors:** *arvindv.tpo@gmail.com*
***DOI:** *https://doi.org/10.7216/teksmuh.1461360* *www.tekstilvemuhendis.org.tr*

1 INTRODUCTION

In recent times, continuous fibre-reinforced composites have seen remarkable progress across various sectors, including automotive, marine, aerospace, and civil engineering [1–4]. However, these advancements come with a challenge: susceptibility to impact loads from sources like runway debris or falling tools, leading to matrix cracks, fibre fracture, and delamination[5]. Addressing this impact resistance issue has become pivotal in composite component design. These composites are indispensable in modern engineering due to their outstanding mechanical properties, lightweight design, and corrosion resistance. Over the years, fibre-reinforced composites, particularly those with glass fibre reinforcement, have gained attention for their strength-to-weight ratios, finding applications in aerospace, automotive, and sports industries. They are also increasingly used in civil engineering for retrofitting concrete and steel structures, seismic retrofitting of bridge piers, and more. Despite their advantages, challenges persist in maintenance and cost aspects [6]. This paper delves into exploring the impact of linear density on the performance of E-Glass thermoset and thermoplastic composites, aiming to provide insights crucial for optimizing their applications in diverse engineering domains.

Composite materials have garnered significant interest due to their potential for exceptional mechanical properties, offering the promise of lightweight yet robust vehicle components [7]. Matrix components of these materials are usually polymers, which can be either thermoplastic or thermosetting [8,9]. Thermoplastic polymers, including polypropylene (PP), polyamide (PA), and polycarbonate (PC), exhibit fluidity at their melting temperatures, defining them as thermoplastics. Composites incorporating these polymers as matrices are termed thermoplastic composites[10,11].Conversely, thermosetting polymers undergo irreversible hardening when exposed to heat, transitioning from a liquid prepolymer or resin. Once hardened, thermosetting polymers, unlike their thermoplastic counterparts, do not melt again and offer high heat resistance and stiffness[12,13]. The aforementioned characteristics render them well-suited for thermoset composites, which are frequently utilized in aerospace sectors that demand exceptional toughness and heat resistance [14-16].High performance Fibre-based composites are normally fabricated from continuous fibre reinforcements embedded in a thermosetting resin[17-19]. Despite the notable mechanical properties of thermoset composites, particularly in terms of heat resistance and toughness, there remains a demand for thermoplastic composites due to their ease of fabrication and high-throughput production capabilities. Polypropylene (PP) is a widely used matrix material in composites due to its cost-effectiveness and mild mechanical qualities [20]. Glass Mat Thermoplastic (GMT) composites, utilizing PP with a glass fibre (GF) mat, exemplify this trend[21,22]. Although GMT composites often employ short fibres in the matrix, with fibre content ranging from 20 to 40 wt%,to enhance mechanical strength and plasticity, they may fall short of meeting industrial requirements[23,24].To address this limitation and enhance the tensile and impact strengths of the composites, longer reinforcement fibres have been introduced into the thermoplastic matrix. The length of these long glass fibres is approximately twice that of the short glass fibres traditionally used in GMT composites. Consequently, composites containing long glass fibres in the thermoplastic matrix exhibit superior mechanical strength and heat resistance [25,26].Currently, the utilization of thermoplastics as matrix materials in structural composites has garnered significant interest owing to its capacity to enhance the efficiency of manufacturing procedures. In contrast to thermosets, thermoplastics exhibit shorter and more straightforward processing cycles, primarily characterized by the removal of chemical reactions through heating and cooling. The adoption of thermoplastics shows potential in decreasing the duration and effort required for shaping in the production of structural composites.Thermoplastic composites typically require a shorter and simpler processing cycle, as their processing mainly deals with heating and cooling of matrix material and involves no chemical reactions [27–29].

The exceptional durability of thermoplastic materials has contributed to their rapid technological advancement [30-33].Prior research has emphasized that thermoplastic matrices exhibit a superior ability to resist delamination compared to their thermosetting counterparts. Composites made of thermoplastics are more resistant to impact because these materials have a higher threshold for damage initiation and energy absorption. An investigation carried out by Carvelli et al. [34]revealed that thermoplastic composites exhibited enhanced toughness beyond the peak value, as well as smoother impact force responses. Furthermore, studies conducted by Nishida and Vieille et al. [35] have presented additional proof of the enhanced mechanical characteristics of thermoplastic composites compared to conventional thermosetting composites when subjected to impact circumstances. The high viscosity of thermoplastic resins presents difficulties in their use, especially when fully impregnating fibre preforms during production, despite the many benefits of these resins.As a result, there is an urgent need to devise strategies for creating composite materials that leverage the strengths of both thermosetting and thermoplastic materials. Hybrid yarns, which combine the matrix and reinforcing elements, not only improve the distribution of thermoplastic resin by decreasing the effective flow distance, but it also allows for simultaneous shaping and impregnation operations [36]. Consequently, this enhances impregnation effectiveness and augments the mechanical properties of the composites [37,38]. Glass, renowned for its lightweight, strength, and durability, plays a pivotal role in various applications. Despite not matching the strength of high-performance fibres, the cost-effectiveness of glass positions it as a compelling alternative.

This study aims to investigate the impact of reinforcement and matrices in two-dimensional woven composites under various strain rate conditions—both quasi-static and dynamic. Two-dimensional woven preforms with consistent areal density were crafted using 600 and 1200 tex linear density of E-glass. Vacuum-assisted resin transfer method (VARTM) was employed for formulating thermoset composites with an epoxy matrix. Conversely, innovative hybrid reinforcements enveloping polypropylene (PP) around a reinforcement core were developed for thermoplastic composites. These reinforcements were used in woven preform fabrication, and the compression molding method produced 2D woven thermoplastic composites. This study thoroughly examines the mechanical behaviour of thermoset and thermoplastic resins, with a specific focus on influence of linear densities. Comprehensive mechanical property analyses, including dynamic impact tests (drop-weight impact and Izod impact) and quasi-static tests (tensile and flexural tests), were conducted to fully characterize these composites. By shedding light on the nuanced mechanical behaviour of these composites, the study significantly contributes to the ongoing advancement of composite materials technology. It lends crucial support to the development of innovative and environmentally friendly solutions across diverse industries.

2 MATERIALS AND METHODS

2.1 Materials

E-Glass roving with linear densities of 600 and 1200 tex were procured from Owen's Corning. A detailed breakdown of the reinforcement properties is presented in Table 1. The matrix fibre chosen for creating hybrid reinforcements and producing hybrid dry-woven fabrics was Polypropylene (PP) multifilament, obtained from Fitpack Textile Mills Ltd. The thermoset resin, Lapox ARL-125 epoxy, and its hardener, AH-367 curing agent, were sourced from Atul Pvt.Ltd.. Properties of the PP matrix material can be referenced in Table 2, while Table 3 provides information on the properties of the thermoset resin and its hardener.

Table 1. Mechanical properties of reinforcement fibres

Fibre	Density (g/cm^3)	Tensile Strength (GPa)	Tensile Modulus (GPa)	Elongation at break (%)
Glass	**2.56**	**1.4-2.5**	**65-72**	**1.8-3.2**

Table 2. Properties of thermoplastic matrix

Description	**Polypropylene**
Linear density (Denier)	840
Density (g/cm^3)	0.91
Tensile strength (MPa)	75
Melt flow index (g/10min)	35
Melting temperature (˚C)	160

Table 3: Properties of thermoset matrix

Description	**Unit**	**Lapox ARL-125 epoxy**	**AH-367 curing agent**
Appearance	Visual	Clear liquid	Clear liquid
Composition	-	Epoxy resin	Modified polyamine
Viscosity	mPa.s	1000-1500	10-50
Density	gm/cc	1.15	0.93-0.99

Table 4. 2D fabric reinforced thermoplastic composite samples

S. No.	**Samples**	**Code**	**FVF (%)**	**Specimen Thickness (mm)**
1	Thermoplastic E-glass (1200 tex)	TP12G2DFRC	50 (2.83)*	5.60 (0.05)
2	Thermoplastic E-glass (600 tex)	TP6G2DFRC	50 (2.46)	5.50 (0.02)
3	Thermoset E-glass (1200 tex)	TS12G2DFRC	50	2.10 (0.02)
4	Thermoset E-glass (600 tex)	TS6G2DFRC	50	2.20 (0.02)

**Standard Deviation*

2.2 Methods

2.2.1 Preparation of the reinforcement/PP hybrid Yarns

Hybrid yarns, combining E-Glass reinforcement and Polypropylene (PP), were manufactured using a co-wrapping approach within a wrap spinning technique. The production involved a hollow spindle spinning machine, where the reinforcement roving, with a predetermined linear density, passed through a roving condenser and inactive drafting rollers. The core roving, lacking true twist, entered the hollow spindle. Simultaneously, PP filament from a spindle-mounted package traversed through the spindle, wrapping around the reinforcement at the core. The high spindle rotational speed induced pseudo-twist in both the reinforcement and PP filament. As depicted in figure 1, the false twist in the E-Glass roving unravelled upon passing through the twisting hook, while the twist in the PP filament wraps was retained. The entire process was carefully executed to maintain a consistent fibre volume fraction of 50% ± 5%. The fibre volume fraction of yarn was determined by calculating weight of components of hybrid yarns.

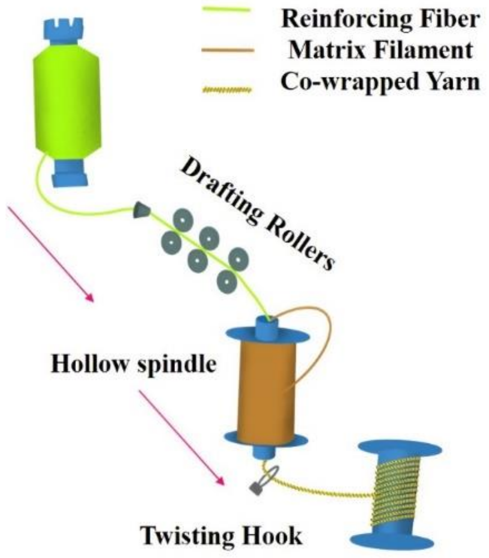


Figure 1. Manufacturing process of hybrid reinforcement by wrap spinning

2.2.2 Preparation of two-dimensional (2D) woven fabrics

Customized rapier weaving looms at the Focus Incubation Centre, Indian Institute of Technology Delhi, were employed to create 2D woven fabrics with a plain weave design. The calculation of ends per inch and picks per inch was meticulous, ensuring the attainment of a constant areal density. Areal density of 600 and 1200 texglass fabrics were 390 gm/m^2 and 593 gm/m^2 respectively. Subsequently, six layers of 600 tex and four layers of 1200 tex glass 2D woven fabrics with areal density aprox. 2400 gm/m^2 were arranged sequentially in a 0-90^0 sequence.

2.2.3 Development of thermoplastic composites

The thermoplastic composites were fabricated through the compression molding technique. Utilizing their corresponding 2D woven preforms, thermoplastic composites incorporating600 and 1200 Tex E-Glass/Polypropylene were developed, which are named as TP6G2DFRC, and TP12G2DFRC (Table 4) respectively. In the manufacturing process, the 2D woven preform was strategically positioned within the mould, sandwiched between Teflon sheets at the top and bottom, and subjected to compression moulding using a machine. Processing conditions involved exposing the composites to a temperature of 185°C and 10 bar (1 MPa) pressure for 10 minutes during full press heating, followed by an additional 10 minutes for cooling, as depicted in Figure 2.

2.2.4 Manufacturing of thermoset composites

The manufacturing process for 2D woven fabric-reinforced composites (2DFRCs) using 2D woven preforms made of 600 and 1200 Tex E-glass filament, employed vacuum-assisted resin transfer molding (VARTM). To optimize outcomes, a resin-to-hardener ratio of 100:32 was determined based on mechanical attribute optimization using the same resin material. The resin-hardener mixture underwent de-airing in a desiccator, involving two two-minute cycles to eliminate any air bubbles before impregnation. Illustrated in Figure 3, the VARTM process delineates the steps involved in producing 2DFRCs. Following resin infusion, the samples underwent vacuum application at a pressure of -1 kg/cm^2, curing for 24 hours at 25°C per the manufacturer's instructions to achieve a high level of handling strength. After the initial curing of 2D woven composites, a post-curing process was initiated at 80°C for 2 hours to ensure that the composite characteristics met the highest quality standards. Thermoset specimens are denoted as TS6G2DFRC and TS12G2DFRC for 600 and 1200 Tex E-glass respectively (Table 4).

Following equation was used to determine composite FVF:

$$\text{FVF\%} = \frac{\frac{Fabric\,weight}{Fiber\,density}}{\frac{Fabric\,weight}{Fiber\,density} + \frac{Resin\,weight}{Resin\,density}} \times 100 \qquad (1)$$

In this equation, FVF% was kept at 50%. Accordingly, the value of resin weight was measured to prepare the composites and achieved the constant FVF% value.

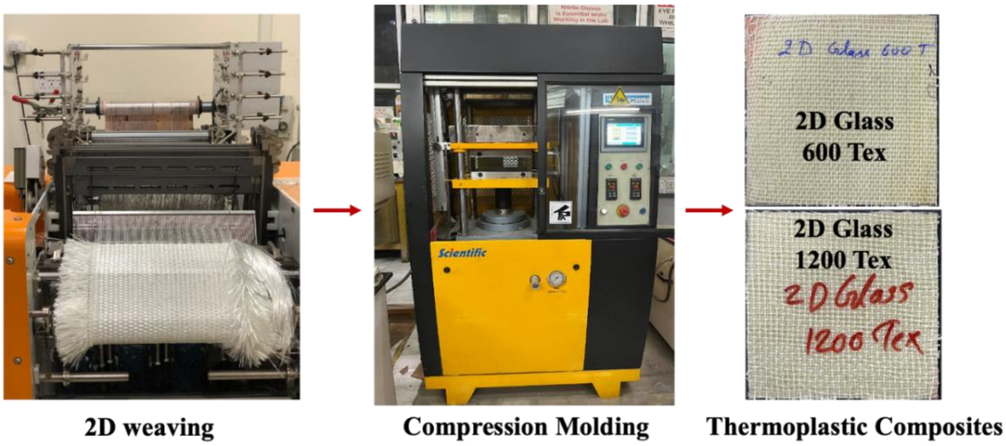


Figure 2. Manufacturing process of 2D woven fabric-based thermoplastic composites

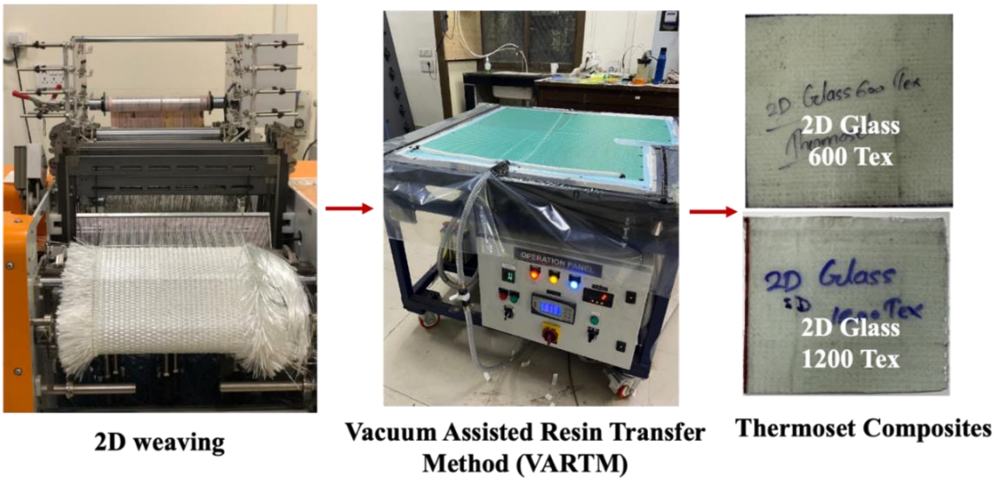


Figure 3. Manufacturing process of 2D woven fabric-based thermoset composites

2.2.5 Characterization of mechanical properties of 2D woven structural composites

2.2.5.1 Tensile test

The tensile testing was carried out using Zwick Roell Z250 UTM with ASTM D3039 standard. The test speed kept was 2 mm/min. Force shutdown threshold was 80% of $F_{max.}$ Load-cell used was 250kN and sample size was 200 mm X 25 mm. Upper force limit was 100 kN and gauge length was 100 mm. Gripping attachment was pneumatic in nature.

2.2.5.2 Flexural (3-point bending) test

The flexural testing was carried out using Zwick Roell Z250 UTM with the ASTM D7264 standard. The test speed kept was 2 mm/min. Force shutdown threshold was 80% of $F_{max.}$ The load-cell used was 25kN and span to thickness ratio was 32:1. Upper force limit was 100 kN and specimen width was 13 mm. Gripping attachment was pneumatic in nature.

2.2.5.3 Edgewise impact test

The edgewise impact test was carried out using Izod Impact (Pendulum type) instrument with ASTM D256 standard. The impact velocity kept was 3.5 m/sec. Pendulum energy and mass was 11 Joule and 1.84 kg respectively. The angle of release was 147.96^0. Sample size was 64 mm X 12.7 mm. Notch-depth length was 2 mm and notch angle was 45^0.

2.2.5.4 Drop-weight impact test

A calibrated INSTRON CEAST 9350 instrument with a 22.4 kN load-cell capacity performed the drop-weight impact testwith ASTM D7136 standard, a common drop-weight impact assessment method. A weight-free-falling, anti-rebound technology prevented several strikes in the testing system. A 12.7 mm-diameter, 10.4390-kg hemispherical steel impactor was dropped without friction from 503 mm at 3.14 m/s with nominal impact energy of 50J. Specimen size was 120mm X 120mm. The study tested damage resistance, the material’s ability to absorb blows before perforation, and a rebound mechanism to prevent repeated collisions. The software was used to analyse the composite specimen’s impact reaction as a time-dependent force, displacement, and energy function.

3 RESULTS AND DISCUSSION

3.1 Tensile behaviour of thermoplastic and thermoset woven composites

In the initial phase, TP6G2DFRC displayed superior tensile modulus within the elastic regime compared to TP12G2DFRC. This regime, reflecting reversible stress-induced deformation, showcased TP6G2DFRC's linear load-bearing progression up to around 2.5% strain. Beyond this point, a slight deviation occurred after reaching peak stress during the hardening phase, resulting in an 8.15% increment. TP12G2DFRC exhibited a similar trend but performed below TP6G2DFRC in both elastic and hardening phases. Notably, TP12G2DFRC continued increasing strain until 12.75% in the hardening phase, avoiding the catastrophic failure observed in TP6G2DFRC, as shown in figure 4.

In thermoset composites, both linear densities demonstrated nearly superimposed behaviour, surpassing thermoplastic composites in load-bearing properties. However, TS6G2DFRC outperformed TS12G2DFRC in both tensile modulus and strength, underscoring the impact of linear density on mechanical properties, as depicted in table 4.The tensile modulus of thermoset composites (TS12G2DFRC and TS6G2DFRC) significantly exceeded that of thermoplastics (TP12G2DFRC and TP6G2DFRC). While TS6G2DFRC and TS12G2DFRC demonstrated similar tensile modulus levels, TP6G2DFRC exhibited a higher modulus than TP12G2DFRC. Tensile strength results echoed this trend, with thermoset composites exhibiting notably higher values. TS6G2DFRC and TS12G2DFRC showcased comparable tensile strength, while TP6G2DFRC outperformed TP12G2DFRC. Figure 5 shows the specimens after performing tensile tests.

The strain at tensile strength for thermoplastic composites surpassed that of thermoset composites, with TP12G2DFRC registering the highest value. This highlights the ductility of thermoplastic composites under tensile loading conditions. Thermoset composites (TS12G2DFRC and TS6G2DFRC) exhibited significantly higher stress at break values compared to thermoplastics (TP12G2DFRC and TP6G2DFRC). Considering modulus, strength, and strain characteristics is crucial when selecting materials for specific applications. The study underscores the superior tensile performance of thermoset composites over thermoplastics, emphasizing the importance of aligning material choices with desired mechanical properties and performance requirements.

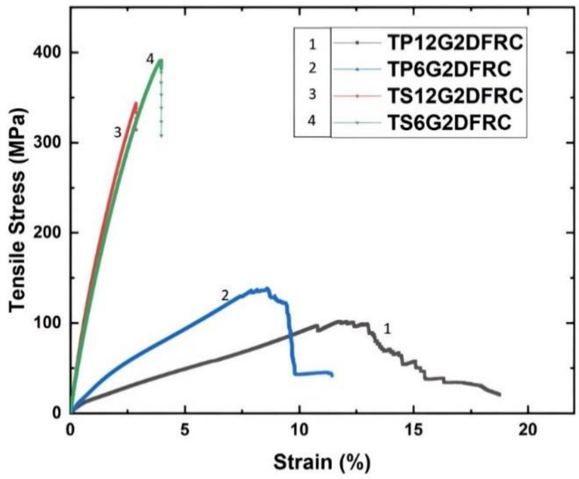


Figure 4: Stress vs strain graph of thermoplastic and thermoset woven composites with different linear densities

Table 5. Tensile properties of 600 and 1200 tex E-glass based 2D woven thermoplastic and thermoset composites

Specimen ID	Tensile modulus	Tensile Strength	Tensile Stress at break	Tensile Strain at Break	Specimen Thickness, h	Specimen Width, b	Cross-sectional Area, A_0
	MPa	MPa	MPa	%	mm	mm	mm²
TP12G2DFRC	2077.93 (22.15)*	102.09 (4.47)*	20.40 (1.45)*	18.75 (1.48)*	5.60 (0.05)*	25	140.00
TP6G2DFRC	3161.58 (20.90)	138.20 (3.47)	41.44 (1.34)	11.43 (1.99)	5.50 (0.02)	25	137.50
TS12G2DFRC	18299.96 (372.61)	343.61 (5.41)	314.21 (8.26)	2.88 (0.12)	2.10 (0.02)	25	52.50
TS6G2DFRC	17433.56 (288.90)	391.43 (9.72)	307.88 (14.17)	3.97 (0.27)	2.20 (0.02)	25	55.00

**Standard Deviation*

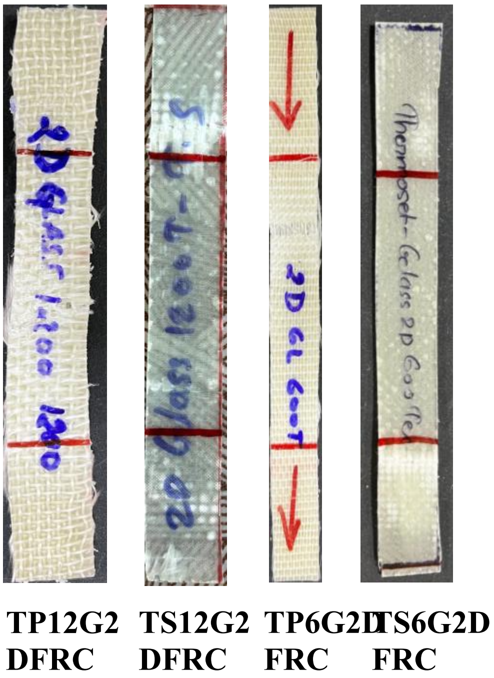


Figure 5. Tensile tested specimens at 2mm/min strain rate

3.2 Flexural behaviour of thermoplastic and thermoset woven composites

Flexural stress in fibre-reinforced composites occurs when bending forces are applied, causing the material to flex and withstand these pressures. When exposed to flexural stress, the composite material experiences both tension and compression on opposite sides of the bend. The fibres in the composite material are responsible for carrying the tensile load, while the matrix is responsible for bearing the compressive load. The manner in which stress is spread out among the fibres and matrix is of utmost importance in determining the flexural characteristics of the material. The linear density of fibres, as highlighted in the study, significantly influences the composite's ability to withstand bending forces, impacting its flexural modulus, strength, and stress at break. The interplay between fibres and matrix in response to flexural stress is a critical consideration in designing and selecting fibre-reinforced composites for applications requiring optimal flexural performance. The linear density of the fibre reinforcement is critical in determining the flexural modulus, strength, and stress at the break of the composite materials. The optimization of composite materials for different purposes relies on a thorough understanding of these features. Two thermoplastic specimens, TP6G2DFRC (600 tex) and TP12G2DFRC (1200 tex), along with two thermoset specimens, TS6G2DFRC (600 tex) and TS12G2DFRC (1200 tex), underwent comprehensive testing to elucidate their flexural characteristics.

With a flexural modulus of 3010.26 MPa, TP12G2DFRC demonstrated a strong ability to resist deformation when subjected to flexural stress. Notably, TP6G2DFRC displayed a higher flexural modulus of 3755.53 MPa, indicating its superior stiffness despite a lower linear density. Turning to the thermoset composites, TS12G2DFRC emerged as the frontrunner with an impressive flexural modulus of 20454.18 MPa, surpassing all other specimens. This exceptional stiffness was closely followed by TS6G2DFRC, which exhibited a flexural modulus of 21142.61 MPa. These results underscore the outstanding stiffness of both thermoset composites, indicating their potential superiority in applications demanding high resistance to flexural stress. In terms of flexural strength, TP6G2DFRC exhibited a strength of 60.81 MPa, surpassing TP12G2DFRC. The thermoset counterparts, TS6G2DFRC and TS12G2DFRC, exhibited even greater flexural strength values of 395.20 MPa and 368.47 MPa, respectively, as shown in table 5. Furthermore, TP12G2DFRC exhibited an impressive tensile strength at fracture of 14.09 MPa, indicating its capacity to endure substantial bending forces prior to breaking. TP6G2DFRC had a fracture strength of 26.20 MPa, demonstrating its ability to withstand and recover from bending stress. Regarding thermoset composites, TS12G2DFRC and TS6G2DFRC stand out for their remarkable stress at break values and capacity to resist flexural loads till failure. Upon analysis of the flexure-strain at break, it was observed that TP12G2DFRC exhibited a value of 18.18%, while TP6G2DFRC had a value of 11.69%. Within the thermoset category, the materials TS12G2DFRC and TS6G2DFRC showed deformation values of 4.10% and 3.55% respectively, suggesting their capacity to endure substantial deformation before reaching the fracture point, as shown in figure 6. This extensive analysis not only offers a valuable understanding of the flexural modulus, strength, and stress at break of thermoset and thermoplastic composites but also highlights the significant impact of linear density on their flexural performance. The results highlight the complex relationship between the structure of fibres and the properties of materials, which helps in adopting the right materials for applications that require excellent bending characteristics. Figure 7 shows the specimens after performing flexural tests.

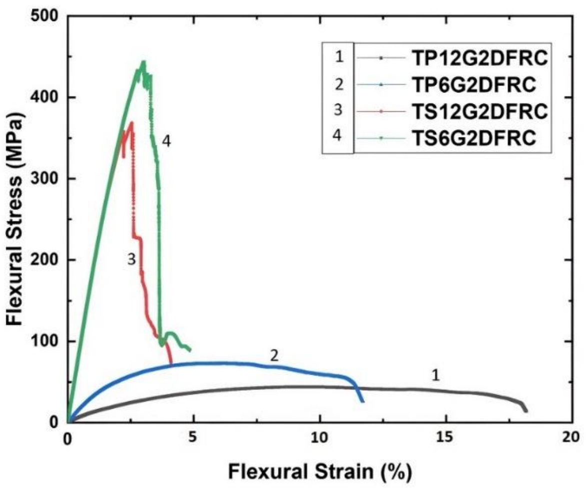


Figure 6: Flexural stress vs strain graph of thermoplastic and thermoset woven composites

Table 6. Flexural properties of 600 and 1200 tex E-glass based 2D woven thermoplastic and thermoset composites

Specimen ID	Flexural Modulus, E_f	Flexural Strength, s_{fM}	Flexural Stress at Break, s_{fB}	Flexure-strain at Break, e_{fB}	Specimen thickness, h	Specimen width, b	Cross-section Area, A_0
	MPa	MPa	MPa	%	mm	mm	mm²
TP12G2DFRC	3010.26 (166.98)*	44.05 (0.67)*	14.09 (0.67)*	18.18 (0.99)*	5.60 (0.05)*	13.00	72.80
TP6G2DFRC	3755.53 (251.86)	60.81 (4.77)	26.20 (1.21)	11.69 (0.35)	5.50 (0.02)	13.00	71.50
TS12G2DFRC	20454.18 (1476.56)	368.47 (15.25)	73.67 (3.33)	4.10 (0.29)	2.10 (0.02)	13.00	27.30
TS6G2DFRC	21142.61 (723.15)	395.20 (11.45)	79.02 (3.88)	3.55 (0.43)	2.20 (0.02)	13.00	28.60

**Standard Deviation*

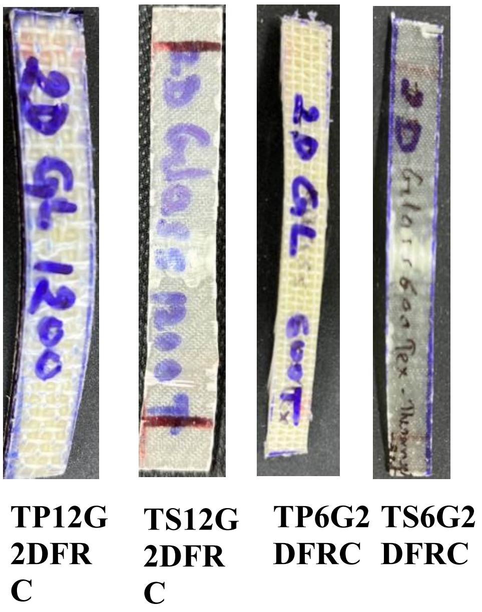


Figure 7. Flexural tested specimens at 2mm/min strain rate

3.3 Edge-wise impact behaviour of thermoplastic and thermoset woven composites

The Izod (in-plane pendulum) impact properties of two different linear densities of E-Glass based thermoplastic and thermoset composites, as indicated by the impact strength and impact energy per notch length, provide insights into their respective performance under impact loading conditions. The examination focused on the edge-wise/Izod impact behaviour of four unique specimens, specifically investigating their impact strength and energy absorption. The thermoplastic composites, TP12G2DFRC and TP6G2DFRC, exhibited higher performance in comparison to their thermoset equivalents.

The thermoplastic woven composites, TP12G2DFRC and TP6G2DFRC, exhibit extraordinary resistance to pendulum impact due to their unique mechanical properties characterized by a high ability to flex and absorb energy through plastic deformation. Thermoplastics possess a distinctive attribute, derived from their molecular structure, that allows them to experience plastic deformation, effectively absorbing and dispersing energy. Thermoplastics have the ability to rearrange their molecules without incurring irreversible chemical changes, which improves their capacity to endure impact, unlike thermosets. The plastic deformation mechanism plays a crucial role in providing thermoplastic composites with excellent impact resistance, distinguishing them from the usually more fragile thermoset counterparts. The enhanced performance of the material is mostly attributed to the inherent features of the matrix, where the higher hardness of thermoplastics enhances its capacity to withstand impact. Thermoplastics possess ductility and the ability to absorb energy, which makes them very efficient in dispersing impact energy and so minimizing disastrous failure. TP12G2DFRC demonstrated an impact strength of 233.69 kJ/m^2 and an impact energy of 2383.62 J/m, but TP6G2DFRC surpassed it with an impact strength of 254.55 kJ/m^2 and an impact energy of 2590.32 J/m. On the other hand, the impact strength and energy of thermoset composites TS12G2DFRC and TS6G2DFRC were lower. Specifically, TS12G2DFRC had an impact strength of 124.04 kJ/m^2 and an energy of 1265.19 J/m, while TS6G2DFRC had an impact strength of 138.56 kJ/m^2 and an energy of 1385.72 J/m, as shown in figure 8. Therefore, unlike thermosets, thermoplastics can rearrange their molecules through plastic deformation, facilitating efficient energy absorption without permanent chemical changes. In contrast, thermoset woven composites, with their cross-linked and rigid molecular structures, are more prone to brittleness. This rigidity makes them less likely to deform plastically under impact forces, increasing the risk of catastrophic failure characterized by crack propagation and fragmentations.

The linear density of reinforcement significantly influenced the impact behaviour. The higher impact strength observed in TP6G2DFRC, despite its lower linear density, suggests that other factors such as matrix toughness and interfacial bonding are significant contributors to impact resistance. The findings emphasize the significance of thoroughly comprehending matrix qualities, reinforcement features, and how they interact to optimize composite materials for improved impact performance. The exceptional impact performance of thermoplastic composites can be ascribed to the intrinsic features of the matrix material. Thermoplastics, which have a greater level of hardness in their structure compared to thermosets, enhance impact resistance. Thermoplastics are more efficient in dissipating impact energy and averting catastrophic failure due to their ductility and energy-absorbing properties. Figure 9 shows the damaged specimens after performing edge-wise impact tests.

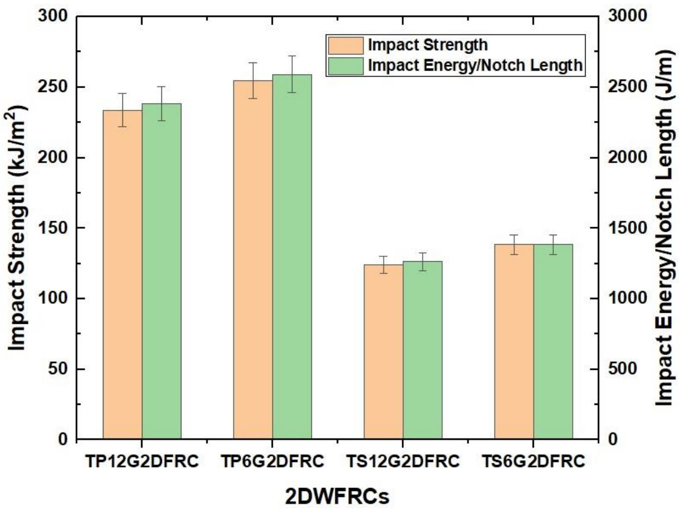


Figure 8. Izod impact properties of thermoplastic and thermoset woven composites

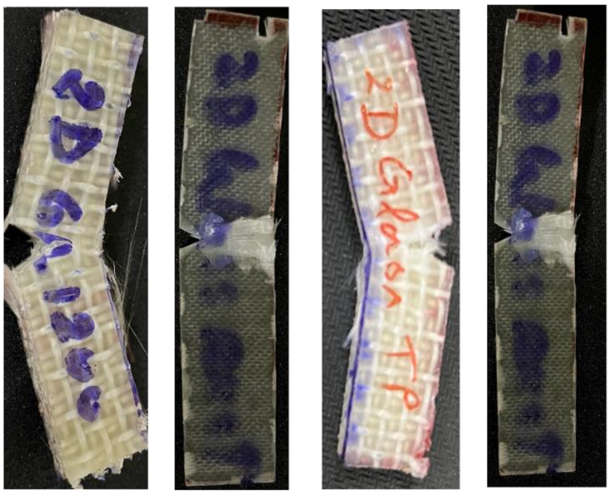

TP12G2DFRC TS12G2DFRC TP6G2DFRC TS6G2DFRC

Figure 9. Izod pendulum impact tested specimens

3.4 Out-of-plane impact behaviour of thermoplastic and thermoset woven composites

A comparative investigation of the low-velocity impact response between thermoplastic and thermoset composites demonstrates clear differences in mechanical behaviours and performance attributes. Thermoplastic composites, which include a molecular structure that enables them to undergo plastic deformation, demonstrate improved ability to absorb energy in the event of impacts. Thermoplastics may deform and transfer energy through this plastic deformation mechanism, which helps prevent damage and lowers the chance of catastrophic failure, as shown in figure 10. In the low-velocity impact scenario, thermoplastic composites displayed superior performance, characterized by their rebound nature and energy absorption capabilities. Analysis of force-time and force-displacement curves revealed a distinct closed curve pattern for thermoplastic specimens, indicating a rebound effect with reduced magnitude after reaching peak force, closing at the end, as depicted in figure 10 (A and C). The energy-time curve further underscored this observation, with the TP6G2DFRC variant exhibiting greater energy absorption compared to TP12G2DFRC, attributed to its lower linear density of the reinforcement. Furthermore, it is worth noting that the TP6G2DFRC exhibited a significantly greater quantity of elastic energy returned to the impactor, highlighting its improved ability to disperse energy in the context of impact events. The velocity vs displacement curves provided empirical evidence supporting the rebound characteristics of both TP6G2DFRC and TP12G2DFRC. These curves exhibited a parabolic shape and showcased enhanced impact resistance, particularly when lower linear density reinforcement was employed, as shown in figure 10(E). In addition, it was observed that thermoplastic composites displayed a considerably higher degree of displacement than their thermoset counterparts. Upon visual examination of the affected specimens, it was noted that there were no observable signs of damage on the front surface of the thermoplastic composites. However, minor dents were detected on the rear surface, and there was no noticeable presence of a back-face signature (BFS), as exhibited in figure 11 (A and B). The results emphasize the advantageous performance of thermoplastic composites when subjected to low-velocity impact events. This is due to their capacity to rebound, absorb energy, and endure displacement, which is particularly noticeable in specimens with lower linear density reinforcement.

On the other hand, thermoset composites, due to their cross-linked and rigid molecular architectures, are more prone to brittle fracture when subjected to low-velocity impact loads. This rigidity limits their ability to undergo plastic deformation, leading to a higher likelihood of crack propagation and fragmentation upon impact. Upon investigating the impact response of thermoset composite specimens, namely TS6G2DFRC and TS12G2DFRC, it becomes apparent that both specimens exhibit a superimposed response across various parameters such as force vs time, energy vs time, velocity vs time, and velocity vs displacement. Notably, both specimens undergo a similar perforation phenomenon. However, the thermoset composite with higher linear density demonstrates marginally higher peak force and greater displacement compared to TS6G2DFRC, as evidenced by the force-displacement curve. Initially, TS6G2DFRC demonstrates superior impact resistance up to the point just before perforation, followed by a sudden drop in force, indicating catastrophic failure. The slope of the ascending section of the curve, known as impact-bending stiffness, elucidates this behaviour. Furthermore, a constant work friction zone is observed after perforation, with TS12G2DFRC exhibiting a more prominent zone compared to TS6G2DFRC. This observation suggests that thermoset composites with higher linear density reinforcement display better resilience against impact loading than those with lower linear density reinforcement.

The work highlights the crucial significance of examining the impact resistance of 2D woven composites using various matrix systems, including thermoset and thermoplastic composites, for advanced engineering purposes. Research has shown that thermoplastic composites are more impact-resistant than other materials. This is because they can be plastically deformed, which allows them to absorb and dissipate impact energy more efficiently, in contrast, thermoset composites have a limited capacity to deform plastically because of their stiff molecular structure, making them more brittle and prone to brittle failure. This comparison highlights the importance of choosing a suitable composite material according to the application's unique needs and performance standards. By understanding the distinct impact response of thermoset and thermoplastic composites, engineers and designers can make informed decisions to optimize the performance and durability of composite structures in diverse engineering applications.

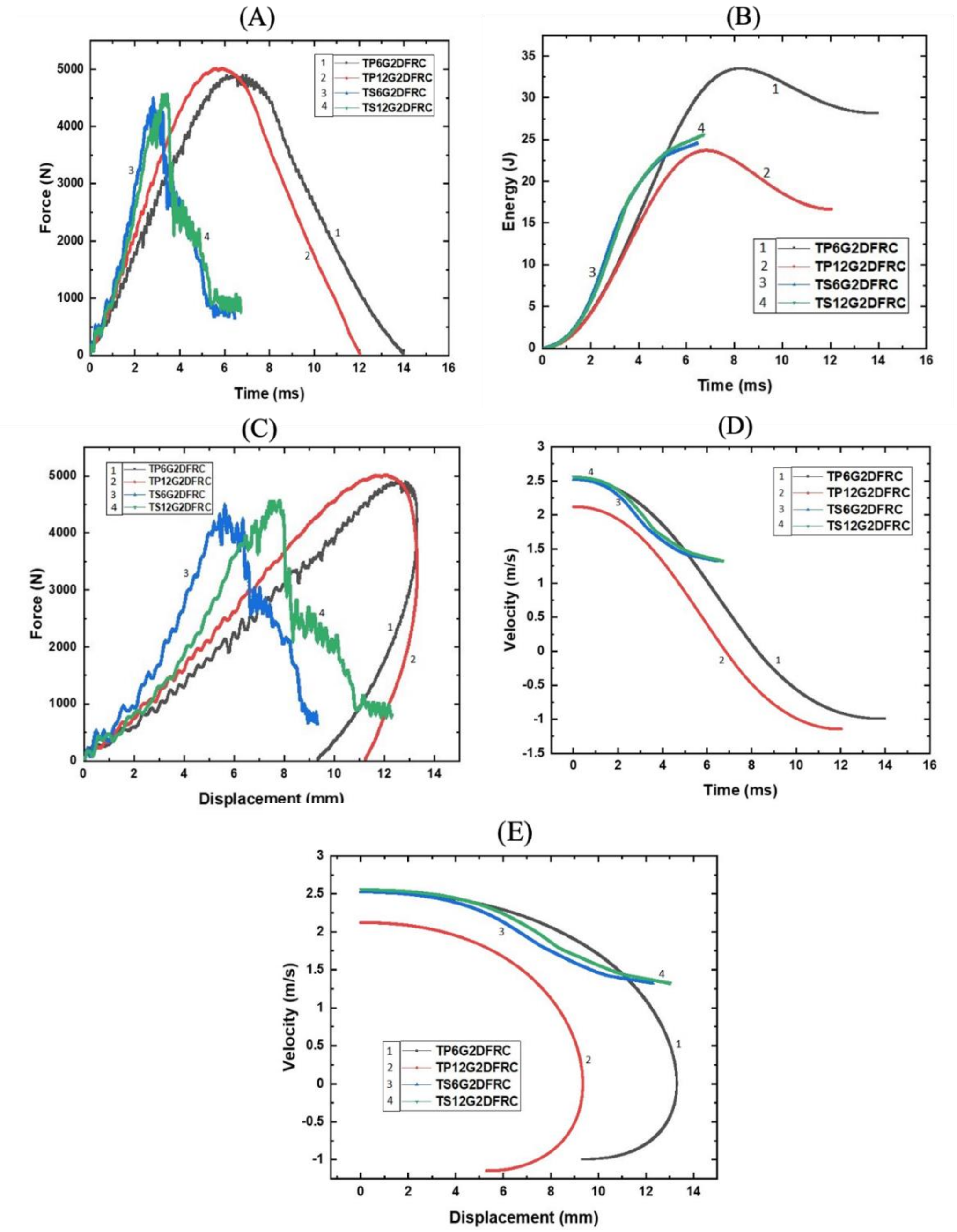
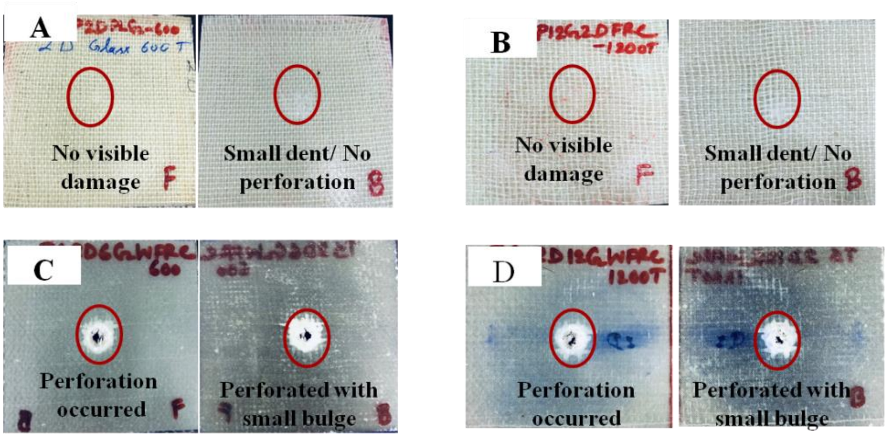


Figure 10. Out-of-plane impact response of thermoplastic and thermoset 2D woven composites, where (A) force vs time, (B) energy vs time, (C) force vs displacement, (D) velocity vs time, and (E) velocity vs displacement



(A) TP6G2DFRC
(C) TS6G2DFRC

(B) TP12G2DFRC
(D) TS12G2DFRC

Figure 11. Out-of-plane impact response of damaged thermoplastic and thermoset 2D woven composites.

4. CONCLUSIONS

In conclusion, this research provides a comprehensive understanding of the mechanical behaviour of 2D woven composites with varying linear densities of E-glass reinforcement, particularly focusing on thermoset and thermoplastic matrices. The study elucidates the nuanced interplay between matrix properties and performance, revealing distinct differences between thermoplastic and thermoset composites.

Thermoset Composites

- Characterized by crosslinked structure.
- Exceptional quasi-static mechanical performance.
- Superior stiffness and dimensional stability.
- Nearly superimposed behaviour with increased linear density, but lower peak force and displacement.

Thermoplastic Composites

- Remarkable resilience in dynamic impact properties.
- Superior tensile modulus within the elastic regime.
- Greater energy absorption and displacement due to ductility and toughness.
- Superior impact resistance despite lower linear density.
- Higher flexural moduli, strengths, and stress at break due to plastic deformation.
- Enhanced energy absorption and resilience against flexural stress.
- Outperformed thermoset counterparts in low-velocity impact response.
- Displayed rebound characteristics and efficient energy dissipation.

Overall, this study emphasizes the importance of material selection based on specific application requirements and performance criteria. By comprehensively understanding the mechanical behaviour of thermoset and thermoplastic composites, engineers can optimize composite structures for diverse engineering applications, ensuring enhanced performance and durability.

REFERENCES

1. Kim D, Jung K, Lee I, Kim H, Structures HK-C, 2017 undefined. Three-dimensional progressive failure modeling of glass fibre reinforced thermoplastic composites for impact simulation. Elsevier n.d.
2. Lu T, Chen X, Wang H, Zhang L, Testing YZ-P, 2020 undefined. Comparison of low-velocity impact damage in thermoplastic and thermoset composites by non-destructive three-dimensional X-ray microscope. Elsevier n.d.
3. Yadav N, Schledjewski R. Review of in-process defect monitoring for automated tape laying. Compos Part A Appl Sci Manuf 2023;173. https://doi.org/10.1016/j.compositesa.2023.107654.
4. Erkendirci ÖF, Haque BZ. Quasi-static penetration resistance behaviour of glass fibre reinforced thermoplastic composites. Compos Part B Eng2012;43:3391–405. https://doi.org/10.1016/j. compositesb. 2012.01.053.
5. Brown KA, Brooks R, Warrior NA. Characterizing the strain rate sensitivity of the tensile mechanical properties of a thermoplastic composite. JOM 2009;61:43–6. https://doi.org/10.1007/S11837-009-0007-9.
6. Mertz DR. Application of Fibre Reinforced Polymer (FRP) Composites to the Highway Infrastructure: Strategic Plan. 2003.
7. Ghayour M, Ganesan R, Engineering MH-CPB, 2020 undefined. Flexural response of composite beams made by Automated Fibre Placement process: Effect of fibre tow gaps. Elsevier n.d.

8. Sun X, Kawashita L, Kaddour A, … MH-C, 2018 undefined. Comparison of low velocity impact modelling techniques for thermoplastic and thermoset polymer composites. Elsevier n.d.
9. Recycling of composite materials. Elsevier n.d.
10. Andrzejewski J, Mohanty A, Engineering MM-CPB, 2020 U. Development of hybrid composites reinforced with biocarbon/carbon fibre system. The comparative study for PC, ABS and PC/ABS based materials. Elsevier n.d.
11. Yang S, Kim Y, Kwon I, Park S, … DK-CPB, 2019 undefined. Simple manufacturing method for a thermoplastic composite using PP-Straw. Elsevier n.d.
12. Guo W, Zhao Y, Wang X, Cai W, Wang J, … LS-CPB, et al. Multifunctional epoxy composites with highly flame retardant and effective electromagnetic interference shielding performances. Elsevier n.d.
13. Wang W, Zhou G, Yu B, Engineering MP-CPB, 2020 undefined. New reactive rigid-rod aminated aromatic polyamide for the simultaneous strengthening and toughening of epoxy resin and carbon fibre/epoxy composites. Elsevier n.d.
14. Nasser J, Zhang L, Technology HS-CS and, 2021 undefined. Laser induced graphene interlaminar reinforcement for tough carbon fibre/epoxy composites. Elsevier n.d.
15. Tripathi L, Chowdhury S, Behera BK. Modelling and simulation of compression behaviour of 3D woven hollow composite structures using FEM analysis. Text Leather Rev 2020;3:6–18. https://doi.org/10.31881/TLR.2020.03.
16. Tripathi L, Chowdhury S, Behera BK. Low-velocity impact behaviour of 3D woven structural honeycomb composite. Mech Adv Mater Struct 2023;0:1–16. https://doi.org/10.1080/15376494.2023.2199415.
17. Behera, B.K., Jain, M., Tripathi, L. and Chowdhury, S. Low-velocity impact behaviour of textile-reinforced composite sandwich panels. Sandw. Compos., 2022, p. pp.213-260. https://doi.org/https://doi.org/10.1201/9781003143031.
18. Chowdhury S, Behera BK. Low-velocity impact response of 3D woven solid structures for multi-scale applications: role of yarn maneuverability and weave architecture. vol. 46. Springer Berlin Heidelberg; 2024. https://doi.org/10.1007/s40430-024-04734-z.
19. Tripathi L, Chowdhury S, Behera BK. Modeling and simulation of impact behaviour of 3D woven solid structure for ballistic application. J Ind Text 2022;51:6065S-6086S. https://doi.org/10.1177/ 1528083720980467.
20. Belingardi G, Beyene A, Structures DJ-C, 2016 undefined. Energy absorbing capability of GMT, GMTex and GMT-UD composite panels for static and dynamic loading–Experimental and numerical study. Elsevier n.d.
21. Behrens BA, Bohne F, Lorenz R, Arndt H, Hübner S, Micke-Camuz M. Numerical and experimental investigation of GMT compression molding and fibre displacement of UD-tape inserts. Procedia Manuf., vol. 47, 2020, p. 11–6. https://doi.org/10.1016/j.promfg.2020.04.109.
22. Dasappa P, Lee-Sullivan P, Xiao X. Temperature effects on creep behaviour of continuous fibre GMT composites. Compos Part A Appl Sci Manuf2009;40:1071–81. https://doi.org/10.1016/j.compositesa.2009.04.026.
23. Behrens BA, Hübner S, Bonk C, Bohne F, Micke-Camuz M. Development of a Combined Process of Organic Sheet forming and GMT Compression Molding. Procedia Eng., vol. 207, 2017, p. 101–6. https://doi.org/10.1016/j.proeng.2017.10.745.
24. Wiese M, Thiede S, Herrmann C. Rapid manufacturing of automotive polymer series parts: A systematic review of processes, materials and challenges. AdditManuf 2020;36. https://doi.org/10.1016/j.addma.2020.101582.
25. Joo SJ, Yu MH, Seock Kim W, Lee JW, Kim HS. Design and manufacture of automotive composite front bumper assemble component considering interfacial bond characteristics between over-molded chopped glass fibre polypropylene and continuous glass fibre polypropylene composite. Compos Struct 2020;236. https://doi.org/10.1016/j.compstruct.2019.111849.
26. Hwang D, Cho D. Fibre aspect ratio effect on mechanical and thermal properties of carbon fibre/ABS composites via extrusion and long fibre thermoplastic processes. J Ind Eng Chem 2019;80:335–44. https://doi.org/10.1016/j.jiec.2019.08.012.
27. Lystrup A. Hybrid yarn for thermoplastic fibre composites. Final report for MUP2 framework program no. 1994-503/0926-50. Summary of technical results. 1998.
28. Zhang L, Miao M. Commingled natural fibre/polypropylene wrap spun yarns for structured thermoplastic composites. Compos Sci Technol 2010;70:130–5. https://doi.org/10.1016/j.compscitech.2009.09.016.
29. Zhang MQ, Rong MZ. Self-Healing Polymers and Polymer Composites. 2011. https://doi.org/10.1002/9781118082720.
30. Pavlovski D, Mislavsky B, Antonov A. CNG cylinder manufacturers test basalt fibre. ReinfPlast 2007;51. https://doi.org/10.1016/S0034-3617(07)70152-2.
31. Li W, Xu J. Impact characterization of basalt fibre reinforced geopolymeric concrete using a 100-mm-diameter split Hopkinson pressure bar. Mater Sci Eng A 2009;513–514:145–53. https://doi.org/10.1016/j.msea.2009.02.033.
32. Li W, Xu J, Zhai Y, Li Q. Mechanical properties of carbon fibre reinforced concrete under impact loading. Tumu GongchengXuebao/China Civ Eng J 2009;42.
33. Liu Q, Shaw MT, Parnas RS, McDonnell AM. Investigation of Basalt Fibre composite mechanical properties for applications in Transportation. Polym Compos 2006;27:41–8. https://doi.org/10.1002/pc.20162.
34. Hao LC, Yu WD. Evaluation of thermal protective performance of basalt fibre nonwoven fabrics. J Therm Anal Calorim2010;100:551–5. https://doi.org/10.1007/s10973-009-0179-0.
35. Czigány T. Special manufacturing and characteristics of basalt fibre reinforced hybrid polypropylene composites: Mechanical properties and acoustic emission study. Compos Sci Technol 2006;66:3210–20. https://doi.org/10.1016/j.compscitech.2005.07.007.
36. Vashishtha A, Sharma D. Mechanical Properties of Natural Fibre-based Woven Fabric- reinforced Thermoplastic and Thermoset Composites 2024;84:320–4.
37. Jiang J, Chen N. Preforms and composites manufactured by novel flax/polypropylene cowrap spinning method. J Compos Mater 2012;46:2097–109. https://doi.org/10.1177/0021998311430155.
38. Study AC. polymers E ff ects of Micro-Braiding and Co-Wrapping Techniques on Characteristics of A Comparative Study. Polymers (Basel) 2020.