

Evaluation of tensile properties in in-plane auxetic carbon/epoxy and carbon-glass/epoxy composite laminates

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Abstract

Auxetic laminates, i.e. with a negative Poisson's ratio (NPR), show great engineering promise, with enhancements in shear resistance, fracture toughness, energy absorption, and delamination and damage extension limitation. This study focuses on the tensile properties of in-plane (IP) NPR fibre-reinforced polymer (FRP) laminates, namely carbon/epoxy (C/E) and carbon-glass/epoxy (C-G/E) laminates, with lay-up sequences which maximised the effect. An analytical study was conducted to achieve maximum NPR sequences. Laminates were manufactured via hand lay-up and hot compression moulding techniques. Poisson's ratios of -0.33 and -0.18 were achieved for C/E and C-G/E IP auxetic lay-ups, respectively. A 72% reduction in longitudinal stiffness between the maximum IP NPR and a unidirectional (UD) lay-up sequence was verified, with a further reduction of 24% from the C/E to the C-G/E auxetic configurations due to less anisotropy from G/E plies. Regarding longitudinal strength, maximum IP NPR sequences showed low failure strengths, with a reduction from 1213 MPa in the UD case, to 209 MPa in the studied C/E laminates. An alternative design sequence was studied analytically with the incorporation of 0° layers in the auxetic sequences, which improved stiffness, albeit at a reduction of IP auxeticity. Further research is recommended to explore alternative auxetic lay-up sequences to study the influence on stiffness, strength, and auxetic enhancements.

Keywords

Auxeticity, composite laminate, metamaterial, Poisson's ratio

Introduction

Composite materials have long been a feature among the highest levels of engineering, especially with the continuous maturation of associated characterisation, manufacturing and certification technologies and systems. Their excellent specific properties - namely stiffness and strength¹ - enable the reduction of weight of a given structure, a factor of particular importance in the mobility sector, as weight saving allows for a decreased need of energy resources.

One of the most commonly used types of composite materials refers to the laminate form, in which several fibre fabric plies are bonded by a matrix. Fibre-reinforced polymers (FRP), such as carbon/epoxy (C/E), glass/epoxy (G/E) or aramid/epoxy (A/E), are widely applied in high-end engineering components, such as in the case of the aeronautic and aerospace sectors. Albeit their desirable specific strength and stiffness, two main issues taint FRP

laminate performance: their low thermal resistance, and their low out-of-plane (OOP) properties due to the absence of reinforcement in the thickness direction. The latter remains a problem for the industry, as such laminates offer

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Data Availability Statement included at the end of the article

sub-optimal low-velocity impact (LVI) resistance, leading to increased susceptibility for the initiation and propagation of barely visible impact damage (BVID), under the form of delamination, i.e. the separation of two bonded plies of distinct fibre orientation, that is hard to detect and that can amount to up to 50% reductions in the laminate's strength. For reference, LVI is a very common occurrence within the aerospace industry, pertaining impacts usually under 10 m/s which are not dominated by stress wave propagation through the material, but rather by elastic energy absorption.² Such impacts can occur during manufacturing - for example, due to tool drops or component mishandling - transportation, storage, installation, and in operation - hailstone strikes, low-velocity bird strikes, runway debris, and belly-landing operations of fixed-wing rotor unmanned aerial vehicles (UAVs).²⁻⁷

The area of metamaterials (MMs), i.e. synthetic composite materials/structures that dispose of properties rarely found in nature, has grown in recent times, with the development of interesting solutions for engineering problems relating to thermal, acoustic, electromagnetic and mechanical cases.^{8,9} A disruptive section within mechanical metamaterials (MMMs) relates to auxetic mechanical metamaterials (AuxMMMs). Auxetics present a unique capacity of synchronous orthogonal compression or dilation - negative Poisson's ratio (NPR) - that translates in property enhancements on shear stiffness, fracture toughness, indentation and impact resistance.¹⁰ AuxMMMs can be further divided into three main groups, with the first concerning lattice structures with specific stiff material patterns capable of auxetic behaviour under loading.¹¹⁻¹⁵ The second group refers to the inclusion of an inherently auxetic element - either matrix, fibre or both - in the metamaterial.^{16,17} The intersection between AuxMMMs and composite laminates results in auxetic laminates, the final category within AuxMMMs, that includes auxetic composite laminates constituted by conventional, i.e. positive Poisson's ratio, fibre(s) and matrix.

Auxetic behaviour is mainly a function of the structural arrangement of plies in a given composite lay-up. Unidirectional (UD) fibre laminae are key for the definition of an auxetic lay-up sequence. Nevertheless, material properties, namely anisotropy - E_x/E_y and E_x/G_{xy} ratios, with E and G as the Young's and shear moduli, respectively, following the axis system set in Figure 1 - unlocks this behaviour and allows for the achievement of larger NPR. The adopted designation for local lamina (x_1 - x_2 - x_3 , or 1-2-3, with x_1 as the fibre direction) and global laminate axis system for this text is depicted in Figure 1.

Auxetic laminates are categorized, in accordance to the NPR plane, as in-plane (IP) - for NPR on the face plane of the laminate (v_{xy}) - or through-the-thickness (TTT) - for NPR along the thickness plane (v_{xz} and v_{yz}). These laminates dispose of an intrinsic deformation mechanism, due to their

NPR and driven by extension-shear coupling, in which, during impact, a local material densification occurs directly under the impacted area as the material flows towards it. Due to these mechanisms, the literature in the area reports improved impact, shear and fatigue resistance in these laminates.^{7,17-22}

Regarding IP NPR, some research has focused on the elastic properties of C/E IP auxetic laminates, either by analytical or experimental means. Table 1 displays a short summary of the analysed properties, with Table 2 exhibiting IP auxetic and reference values for longitudinal strength, X_f^T , and strain-to-failure, ε_{fx}^T .

In this paper, the elastic and failure tensile properties of C/E and carbon-glass/epoxy (C-G/E) IP auxetic lay-ups have been analysed. This evaluation is an important step for the application of IP auxetic sequences in components which sustain LVI and are prone to delamination damage, as the understanding of the tensile properties is relevant with regards to stiffness, strength and other aspects of mechanical design beyond impact resistance. The largest NPR yielding C/E and C-G/E - constituted by T300 carbon and E-glass fibres, and SR8500 epoxy resin - lay-up sequences were selected from a pool of analytically studied bidirectional ($[(\theta_1/\theta_2)_n]_S$) lay-ups¹ symmetric architecture.

Two reference groups, with respect to UD C/E and G/E laminates, were selected for comparison and for validation the selected properties for fibres and resin, based on literature. As for the IP NPR groups, a C/E group was inferred as a direct comparison to the C/E control group. The hybrid C-G/E IP NPR group presents a direct comparison against the C/E auxetic group, to verify the effect of the insertion of G/E plies in the laminates. Moreover, to this point, no literature has experimentally verified the effect of hybridisation in auxeticity of laminates. Carbon and glass hybridisation is commonly applied and is relevant in the engineering world, thus its merge with the auxetic domain could prove beneficial.

Tensile tests were conducted according to the ISO 527-4 standard at a velocity of 2 mm/min, using video-extensometry techniques for the assertion of strains ε_x and ε_y . An evaluation of elastic longitudinal and transverse properties, and concurrently, of longitudinal and transverse tensile strengths, X_f^T and Y_f^T , and of longitudinal and transverse strain-to-failure, ε_{fx}^T and ε_{fy}^T , is performed.

This study intends to provide, thus, an overview into the tensile behaviour of C/E and C-G/E bidirectional laminates with maximum IP NPR, and to analyse any possible drawbacks inherent to this auxetic design strategy.

Methodology

The methodology employed for this study can be divided in material selection, definition of composite lay-up architecture,

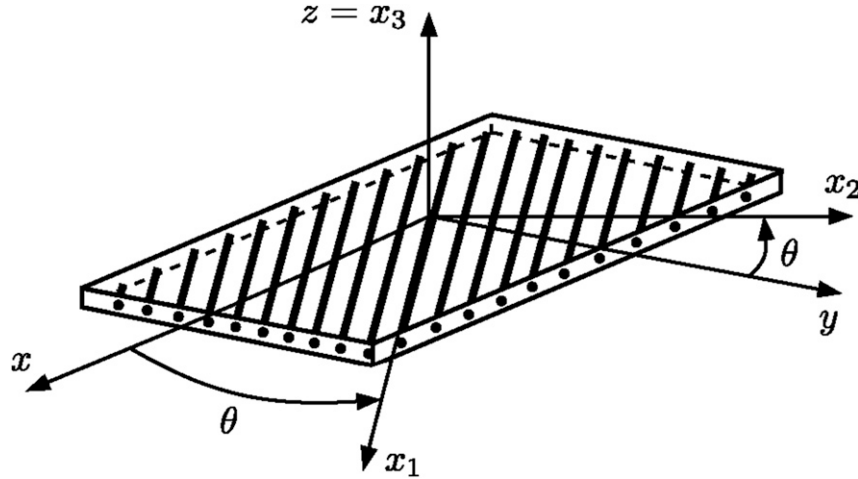


Figure 1. Adopted direction notation.

Table 1. Elastic properties of C/E IP auxetic laminates found in literature.

Lead author	Material	Lay-up sequence	ν_{xy}	E_x (GPa)	E_y (GPa)	G_{xy} (GPa)
M. Miiki ²³	T300/5208	$[(14^\circ/62^\circ)_n]_s$	-0.380	—	—	—
R. Zhang ²⁴	T300/5208	$[(15^\circ/62.5^\circ)_n]_s$	-0.326	—	—	—
M. Shokrieh ²⁵	T300/5208	$[(15^\circ)_2/(60^\circ)_1]$	-0.354	—	—	—
J. Donoghue ¹⁸	AS4/3501-6	$[0^\circ/15^\circ/75^\circ/15^\circ]_s$	-0.134	63.4	27.2	6.29
C. Goncalves ²⁶	Grafil 34-700/CR83	$[0^\circ/15^\circ/75^\circ/15^\circ]_s$	-0.120	53.4	—	—
W. Lin ²⁷	IM7/8552	$[15^\circ/65^\circ/15^\circ/65^\circ/15^\circ]_2$	-0.410	52.1	25.5	6.16

Table 2. Tensile failure properties of C/E IP auxetic laminates, and respective control groups, found in literature.

Lead author	Material	Lay-up sequence	ν_{xy}	X_f^T (MPa)	ε_{fx}^T (%)
C. Goncalves ²⁶	Grafil 34-700/CR83	$[0^\circ/15^\circ/75^\circ/15^\circ]_s$	-0.120	468	1.08
		$[0^\circ]_8$	0.330	1172	1.16
W. Lin ²⁸	IM7/8552	$[15^\circ/65^\circ/15^\circ/65^\circ/15^\circ]$	-0.410	306	0.61
		$[35^\circ/60^\circ/-5^\circ/60^\circ/35^\circ]$	0.134	567	1.04

the analytical inference on the maximization of IP NPR, composite lay-up production and discretization of tensile test parameters. Each of these topics is described in the subsequent subsections.

Material selection

Two distinct fiber types, carbon and glass, were selected based on their cost-effectiveness and engineering significance. The fibre fabrics were chosen to meet the pre-determined conditions for achieving NPR, specifically requiring UD fabrics. For carbon, a T300-fibre 12K UD fabric with an areal weight of 320 g/m^2 , supplied by *Rebelco*, was selected. For glass, an E-glass UD fabric with an areal weight of 640 g/m^2 , provided by *Saertex*, was used.

The respective fibre properties are displayed in Table 3, as referenced by Soden et al.³¹

With regards to the matrix, this research focused on thermosetting resins, namely epoxies. The resin system chosen for this study was supplied by *Sicom* - SR8500 resin and SZ8525 hardener. The adopted properties for this system are shown in Table 4, based on supplier recommendations and values from Soden et al.³¹.

Definition of composite lay-up architecture

Four distinct groups were defined for study, with the referencing scheme presented in Table 5. This scheme consisted of two control groups, one for each fabric type, with a full UD lay-up of carbon (reference K) and glass (reference

Table 3. T300 and generic E-glass fibre (subscript *f*) elastic properties.³¹

Fibre type	T300	E-glass
Density, ρ (g/cm ³)	1.76	2.54
Longitudinal modulus, E_f (GPa)	230	74
Transverse modulus, E_{f2} (GPa)	15	74
IP shear modulus, G_{f12} (GPa)	15	30.8
Major Poisson's ratio, ν_{f12}	0.2	0.2
OOP shear modulus, G_{f23} (GPa)	7	30.8

Table 4. SR8500/SZ8525 adopted matrix (subscript *m*) mechanical properties.

Resin/hardener	SR8500/SZ8525
Density, ρ (g/cm ³)	1.12
Elastic modulus, E_m (GPa)	3.15
Shear modulus, G_m (GPa)	1.17
Major Poisson's ratio, ν_m	0.35

Table 5. Tensile specimen reference scheme.

Reference	Material	Group
A	C/E (carbon/epoxy)	IP NPR
B	C-G/E (carbon-glass/epoxy)	IP NPR
K	C/E (carbon/epoxy)	UD Control
L	G/E (glass/epoxy)	UD Control

L). Two more groups were defined for IP NPR lay-ups, one for C/E laminates - reference A - and one for hybrid C-G/E laminates - reference B. Another reference was considered for glass/epoxy (G/E) IP NPR laminates, however, as discussed subsequently, the analytical analysis developed showed no results for auxeticity in such laminates. Control groups were defined as UD, in this study, mainly in order to control the elastic properties calculated analytically in the subsequent sections, and to infer on the properties selected from Tables 3 and 4.

The fibre volume fraction, ν_f , was defined at this stage, based on values in current use in the aerospace industry. Harkati et al.³² pointed an interval of $\nu_f \in [65;80]$ %, with the selection of this study falling on the lower limit in order to maximize NPR.²⁹ Moreover, for G/E plies, this relation was further decreased to 60% for the same purpose, to maximize NPR in the hybrid reference while maintaining similar processing conditions as to those in C/E references.

The lay-up sequence was specified as bidirectional, in accordance to the aforementioned literature on the topic which indicated that this sequence yields the maximum NPR effect.²² The following subsection describes the

employed analytical methodology to assert the most auxetic sequences for C/E and C-G/E specimens with the referenced fibres and resin system, based on the possible domain of bidirectional symmetric lay-ups - $([(\theta_1/\theta_2)_n]_s)$.

Additionally, for the case of hybrid sequences, not only the fibre angle of each ply has to be defined, but also the respective material. The total number of laminae, N_L , was restricted to a multiple of 8 in order to allow for a correct match between angle and hybrid material lay-up sequences. The number of plies for NPR references was set as 16 accordingly, and a material configuration of $[(\mathbf{M}_1)_2/(\mathbf{M}_2)_2]_{N_L/8}_s$ was adopted, with $\mathbf{M}_1$ and $\mathbf{M}_2$ referencing each possible material for a given ply, which in this case refers to G/E and C/E plies, respectively. This material configuration was selected in order to simplify the combined effect of ply angle and material for this study - two plies of G/E for each bidirectional angle combination, followed by two plies of C/E. A visual representation of the hybrid lay-up scheme is shown in Figure 2.

Analytical elastic constant prediction

A preliminary evaluation of auxetic behaviour in C/E T300/8500, G/E E-glass/8500 and C-G/E T300+E-glass/8500 $([(\theta_1/\theta_2)_n]_s)$ laminates was performed in a computational algorithm developed in MATLAB, based on a micro and macromechanics analysis of a laminate.²⁹ The micromechanics section concerns the definition of nine elastic lamina constants ($E_1, E_2, E_3, G_{12}, G_{13}, G_{23}, \nu_{12}, \nu_{13}$ and ν_{23}) and their insertion on a formulation for effective properties estimated using Maxwell's methodology.³⁰ Macromechanics - at the laminate level - makes use of the Classical Lamination Theory (CLT) and 3D constitutive equations, calculating $E_x, E_y, G_{xy}, \nu_{xy}$ and ν_{xz} , with material invariants and geometric factors relevant to the calculation of the extensional stiffness matrix of each laminate.

The calculated lamina properties for a ν_f of 65%, in C/E laminae, and 60%, in G/E laminae, are displayed in Table 6. As noted in the Introduction, there is a large discrepancy in anisotropy between C/E and G/E plies (E_1/E_2), indicating a larger predisposition to the development of NPR in C/E-based laminates.

Data in Table 6 served as input for the macromechanics module. The algorithm was set for the calculation of all possible bidirectional symmetric $([(\theta_1/\theta_2)_n]_s)$ laminates, with a θ in the range of $[-90^\circ;90^\circ]$ in 0.1° intervals, accounting for 3243601 iterations for each material combination. For C-G/E laminates, a material ($\mathbf{M}$) lay-up sequence of $[(\mathbf{M}_1)_2/(\mathbf{M}_2)_2]_{N_L/8}_s$ was employed. The results, pertaining the largest auxetic IP configurations, are presented in Table 7. No IN NPR was achieved in G/E laminates. Moreover, there is a noticeable decrease in the largest ν_{xy} for C-G/E laminates due to the insertion of less anisotropic G/E plies. A similar trend can be observed for E_x .

Furthermore, and comparing IP C/E NPR laminates with the UD case previously presented in Table 6, there is a decrease in E_x and increase of G_{xy} due to the necessary orientation ply angles for the maximization of IP NPR.

From these analytical results, the auxetic references, in accordance to Table 5, were selected. The C/E IP NPR reference A was defined as a $[(14^\circ/64^\circ)_{n,s}]$ lay-up, while for the C-G/E IP NPR reference B, the selected lay-up sequence was $[(15^\circ/69^\circ)_{n,s}]$ (Table 8).

Composite lay-up production

The four indicated references shown in Table 5 were manufactured in the form of plates using hand lay-up and

G/E	θ_1	Symmetry line
G/E	θ_2	
C/E	θ_1	
C/E	θ_2	
G/E	θ_1	
G/E	θ_2	
C/E	θ_1	
C/E	θ_2	

Figure 2. Adopted hybrid lay-up angle and material scheme.

hot compression moulding techniques. The overall process consisted on the hand lay-up placement and impregnation of angled plies - according to each lay-up sequence - using the SR8500/SZ8525 resin/hardener system at a 4:1 weight ratio. In the case of control references, these were used mainly for property control, and thus 8 plies were utilised in order to promote failure at lower tensile loads, given maximum load limitations in the used tensile test machine (detailed in the subsequent section). For IP NPR groups, 16 plies were applied to each laminate.

Each of these plates was later cured by hot compression moulding at a temperature of 110°C during 10 min, in a *Fontjine LabManual 300* press. Pressure was controlled in order to achieve the aforementioned 65% fibre volume fraction value for the laminates - beside the 60% target for the G/E laminate. This target was not achieved - values were slightly lower, see Table 8 - however this did not compromise the remainder of the study, as no large discrepancies to the target and between references were verified, and as the corresponding adjusted elastic properties were calculated from the analytical algorithm.

Plates were cut to specimen size in accordance with the ISO 527-4 standard (250 mm $\times$ 25 mm). For IP NPR references, additional specimens were cut in the transverse direction for measurement of transverse laminate properties.

Table 6. Material properties of T300/8500 and E-glass/8500 laminae.

Lamina material	E-glass/8500 ($\nu_f = 0.60$)	T300/8500 ($\nu_f = 0.65$)
E_1 (GPa)	45.7	151
E_2 (GPa)	10.5	7.98
G_{12} (GPa)	4.10	4.10
ν_{12}	0.252	0.248
ν_{21}	0.0576	0.0131
ν_{13}	0.252	0.248
ν_{23}	0.442	0.331

Table 7. Largest IP NPR yielding configurations for T300/8500 C/E and T300+E-glass/8500 C-G/E bidirectional symmetric $[(\theta_1/\theta_2)_{n,s}]$ laminates.

Material	ν_{xymin}	$[(\theta_1/\theta_2)_{n,s}]$	E_x (GPa)	E_y (GPa)	G_{xy} (GPa)	ν_{xz}
T300/8500	-0.412	$[(14.0^\circ/63.6^\circ)_{n,s}]$	46.1	22.7	5.69	0.498
T300+E-glass/8500	-0.196	$[(15.1^\circ/68.6^\circ)_{n,s}]$	36.2	26.9	5.55	0.480

Table 8. Discretization of tensile tested references.

Reference	Material	Configuration	Group	ν_f	t_L (mm)
A	C/E	$[(14^\circ/64^\circ)_{n,s}]_4$	IP NPR	0.61	4.64 ± 0.04
B	C-G/E	$[(15^\circ/69^\circ)_{n,s}]_4$	IP NPR	0.58	4.06 ± 0.07
K	C/E	$[0^\circ]_8$	UD Control	0.61	2.24 ± 0.03
L	G/E	$[0^\circ]_8$	UD Control	0.58	2.18 ± 0.03

$[0^\circ/90^\circ]_3$ G/E unbeveled end tabs were applied after surface sanding, with a length of 75 mm, in order to prevent slipping during tensile testing. For this, the matrix/hardener combination SR Greenpoxy 33/SZ 8525 was applied, with similar properties to the SR8500 resin but with a room temperature curing process of approximately 7 h.

Tensile test parameters

Tensile experiments were conducted on a *MTS Exceed E45* tensile testing machine prepared to carry out measurements using videoextensometry techniques with an *MTS AVX-205* camera, with a resolution of $0.25 \mu\text{m}$ and a maximum capture rate of 30 Hz (Figure 3). As aforementioned, the standard ISO 527-4 was employed, with a testing velocity of 2 mm/min. A load cell of 100 kN was used, with an accuracy of $\pm 0.5\%$ of applied force. For IP NPR references, two distinct tensile tests were conducted in the axial and transverse directions. For each reference and specimen orientation, a total of five specimens were tested. The nomenclature, fibre volume fraction, and thickness (t_L , with subscript L referring to the laminate) for the tested specimen groups is presented in Table 5.

Videoextensometry-related preparations included coating the specimens with matte spray, and the marking of two points x and y directions, each at an 8 mm distance to the centreline, totaling a 16 mm gauge length for the virtual extensometers.

Force data was read every on a 5 Hz frequency, while ε_x and ε_y were measured with a 20 Hz frequency. Data was re-sampled in order to accommodate this discrepancy, to the lowest data reading frequency in the system (force). σ_x - ε_x , σ_y - ε_y and ν_{xy} - σ_x relationships, X_f^T and Y_f^T tensile strength, and ε_{fx}^T and ε_{fy}^T strain-to-failure were computed from the processed data.

E_x and E_y were retrieved from a linear curve fit in the elastic loading portion of the respective σ_x - ε_x and σ_y - ε_y specimen graphs.

As for ν_{xy} predictions, the presented experimental values were calculated taking into account the average within a selected region of the elastic domain, as there was, in some cases, a considerable variation of ν_{xy} with the increase of σ_x , as previously denoted in a study by Zhang et al.³³. Although in this study a 100 MPa baseline for ν measurement was defined, the averaged method was preferred for this study given the variation of this property, in order to provide a reliable value, in accordance with the ν_{xy} - σ_x behaviour.

Moreover, the initial phase of the elastic domain was neglected for the calculation of the average ν_{xy} due to an unreasonable amount of noise data. This initial variation can be attributed to the accommodation of the G/E end tab interface to the machine's grips. Due to operational limits, the full specimen's end tab length could not be gripped,

leading to the non-gripped length eventually "opening up" and separating from the specimen during the trials, which caused initial instability in the data. Nevertheless, the remaining gripped length remained bonded and prevented slippage.

Results

Tables 9 and 10 display predicted and experimental values of the longitudinal and transverse elastic modulus, E_x and E_y , respectively. Moreover, longitudinal - X_f^T and ε_{fx}^T - failure properties are exhibited for the tested configurations, and transverse - Y_f^T and ε_{fy}^T - failure properties are shown for IP NPR references. All the predicted values presented herein were calculated using the aforementioned MATLAB algorithm, taking into account adjusted ν_f values for each group, in accordance to those shown in Table 8.²

UD control groups K and L presented very good agreement with predicted E_x values. With regards to IP NPR groups A and B, an overestimation of longitudinal stiffness was evidenced by the experimental results, a trend repeated in the transverse analysis for E_y .

Figure 4 portrays a bar chart of E_x for the tested groups. Figures 5 and 6 represent the stress-strain behaviour in the longitudinal and transverse directions, respectively. Comparing groups K and A, there is a reduction in the longitudinal stiffness of auxetic C/E IP specimens comparing to the UD case of 72%, from 141 GPa to 39 GPa, justified by the C/E ply orientations - at 14° and 64° - required to maximise the auxetic effect, which promotes said reduction. Although the transverse stiffness, E_y , was not measured experimentally for control groups, it is expected to increase in the C/E IP NPR group compared to the UD case (as observed by the predictions indicated in Tables 6 and 7). Moreover, as expected, a reduction in E_x of 24% was verified from the C/E to the C-G/E IP NPR groups A and B, from 39 GPa to 30 GPa, due to the inclusion of less stiff G/E plies, when compared to C/E ones.

Regarding longitudinal tensile strength, X_f^T , it is, as expected, lower in UD G/E - at 660 MPa - than in UD C/E laminates - at 1.21 GPa. Conversely, the less anisotropic nature of glass fibres allow for larger strain-to-failure values, ε_{fx}^T . Regarding IP NPR groups, an important trend was retrieved from data: their strength capacity in the longitudinal direction is much lower than in the control groups. While in the case of the UD C/E control group this value sits at 1.21 GPa, it drops to 209 MPa in the IP NPR C/E group, reducing to 204 MPa for the IP NPR C-G/E group.

These findings corroborate with those of the limited research on the area. A recent study conducted by Lin and Wang, in which an IP auxetic configuration was compared against a non-auxetic variant with matched elastic moduli,



Figure 3. MTS Exceed E45 tensile testing machine with AVX-205 camera.

Table 9. Predicted and experimental longitudinal elastic modulus, E_x , and experimental longitudinal tensile strength, X_f^T , and strain-to-failure, ϵ_{fx}^T , of the tested configuration groups.

Specimen group	E_x (GPa)		X_f^T (MPa)	ϵ_{fx}^T (%)
	Predicted	Experimental		
A (C/E IP NPR)	43.11	39.51 ± 1.93	208.8 ± 6.1	0.8622 ± 0.1615
B (C-G/E IP NPR)	33.46	29.93 ± 1.98	204.3 ± 3.4	1.051 ± 0.137
K (C/E UD)	141.5	141.3 ± 6.0	1213 ± 138	0.8961 ± 0.0495
L (G/E UD)	44.26	44.39 ± 3.47	660.3 ± 33.6	1.589 ± 0.065

also verified low strength properties in IM7/977-3 C/E IP auxetic laminates.²⁸ The authors compared an IP auxetic lay-up sequence - $[15^\circ/65^\circ/15^\circ/65^\circ/15^\circ]$, with a ν_{xy} of -0.410 - to a matched-moduli sequence with a positive IP Poisson's ratio (see Table 2). A decrease in the ultimate tensile strength of IP NPR specimens was confirmed, from

567 MPa to 306 MPa, coupled with lower strain-to-failure values (1.04% vs 0.61%, respectively, both representing a reduction to a 1.61% failure strain in the UD case). Another study by Goncalves et al., using Grafil 34-700/CR83 C/E laminates, compared the tensile properties of an IP auxetic configuration, $[0^\circ/15^\circ/75^\circ/15^\circ]_s$, to an UD counterpart

Table 10. Predicted and experimental transverse elastic modulus, E_y , and experimental transverse tensile strength, Y_f^T , and strain-to-failure, ε_{fy}^T , of the tested configuration groups.

Specimen group	E_y (GPa)		Y_f^T (MPa)	ε_{fy}^T (%)
	Predicted	Experimental		
A (C/E IP NPR)	23.15	21.57 ± 1.29	125.2 ± 7.3	1.520 ± 0.078
B (C-G/E IP NPR)	27.32	23.36 ± 2.65	139.5 ± 2.2	1.174 ± 0.207

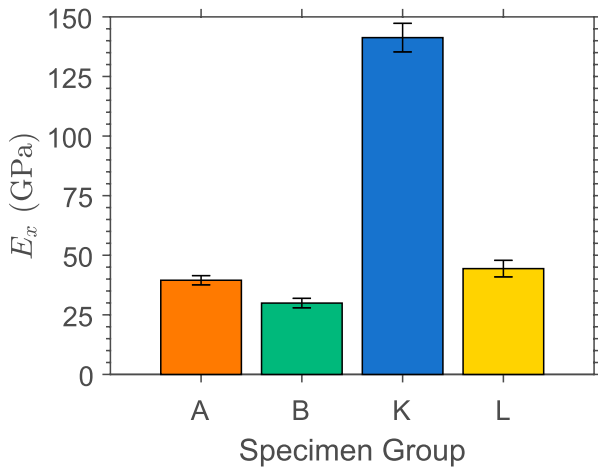


Figure 4. Experimental longitudinal elastic modulus, E_x , bar charts for groups A (C/E IP NPR), B (C-G/E IP NPR), K (C/E UD) and L (G/E UD).

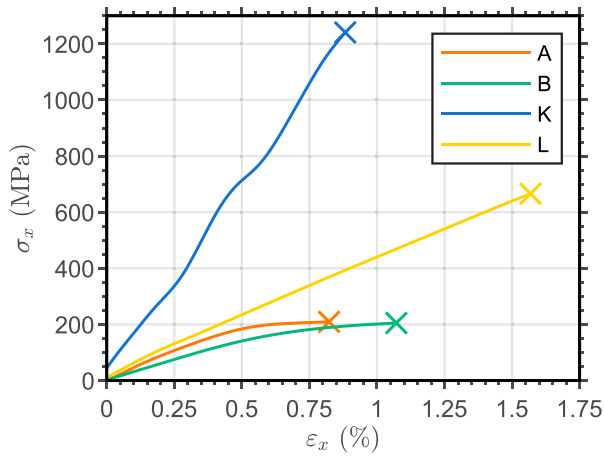


Figure 5. Longitudinal stress-strain curves for groups A (C/E IP NPR), B (C-G/E IP NPR), K (C/E UD) and L (G/E UD).

(Table 2). Both the ultimate longitudinal tensile strength, and the strain-to-ratio, were lower in the IP NPR lay-up, at 468 MPa versus 1172 MPa, and at 1.08% versus 1.16 %, respectively. Thus, the lay-up configuration required for the maximisation of IP auxeticity affects its longitudinal tensile strength capabilities negatively.

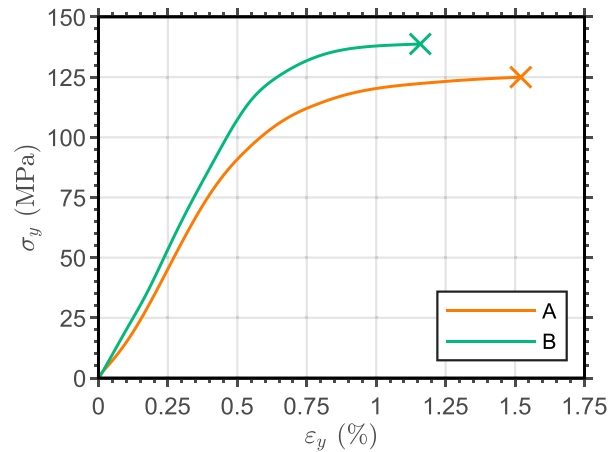


Figure 6. Transverse stress-strain curves for groups A (C/E IP NPR) and B (C-G/E IP NPR).

Figure 7 shows the post-mortem samples of each group. For specimens in which failure occurred, the failure plane followed fibre direction, as weak resin-rich planes are developed in between fibre bundles with the increasing elongation of the specimen, hence enabling the development of failure planes in such areas. In UD C/E and G/E specimens of group K and L, 0° orientation cracks are visible, with internal delamination. For the control C-G/E group, severe fibre breakage of the top G/E plies was verified. For IP NPR specimens, a crack is observable along the angle of the top ply.

It should also be noted that the nature of the T300 carbon and E-glass fabric fixation - with evenly spaced weft yarns - creates a prelude condition for the formation of failure planes: as various carbon or glass bundles are grouped by such weft yarns, a small gap between such bundles can become more evident with fabric handling, and can be solely filled by resin during impregnation, creating a local weak point that favours the development of failure planes and that can affect strength properties, especially in laminates that do not possess 0° - to better sustain the applied load in the axial direction - or 90° layers.

With regards to IP NPR results, Table 11 presents predicted and experimental ν_{xy} for the tested configurations. Figure 8 displays the respective bar charts.

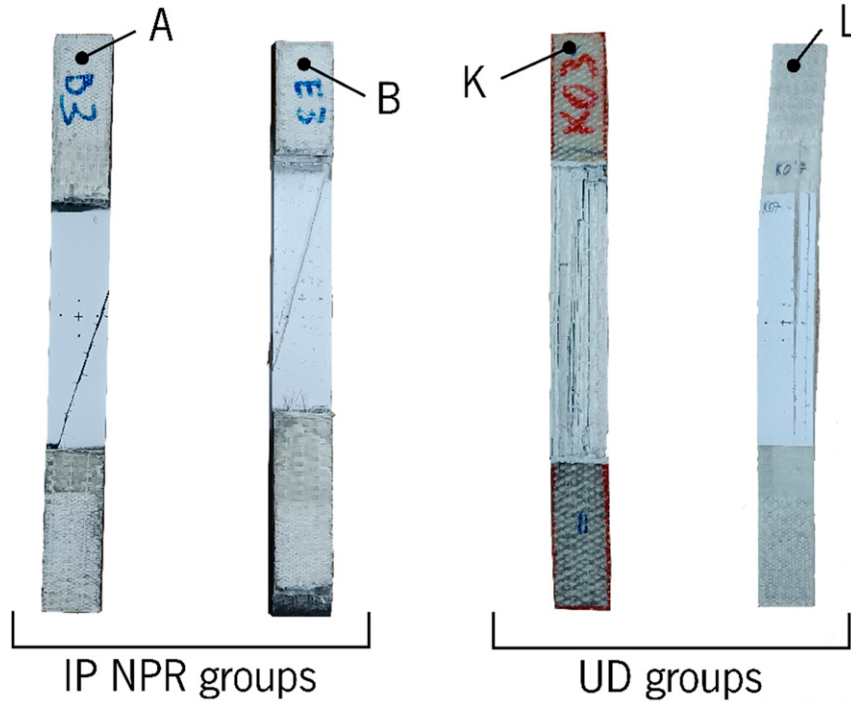


Figure 7. Failure planes of tested specimen configurations A (C/E IP NPR), B (C-G/E IP NPR), K (C/E UD) and L (G/E UD).

Table 11. Predicted and experimental IP Poisson's ratio, ν_{xy} , of the tested configuration groups.

Specimen group	ν_{xy}	
	Predicted	Experimental
A (C/E IP NPR)	-0.4150	-0.3328 ± 0.0241
B (C-G/E IP NPR)	-0.2013	-0.1793 ± 0.0383
K (C/E UD)	0.2540	0.3408 ± 0.0760
L (G/E UD)	0.2544	0.3311 ± 0.0208

Data evidences a larger discrepancy between predicted and experimental values for ν_{xy} , when compared to the previous E_x analysis. The predictions for UD specimens present a considerable deviation to the experimentally obtained values. This trend was also verified for group A, with the closest prediction relating to the one for group B. Moreover, IP auxeticity was overestimated with the predicted values.

Nevertheless, auxeticity was experimentally achieved for both IP NPR groups, as visible in Figure 9, portraying the stable domain for the $\nu_{xy} - \sigma_x$ relationship of groups A and B. A slight increase in auxeticity was verified for IP NPR groups with increasing σ_x in the elastic region: as the specimens were continuously stretched in the longitudinal tensile direction, an increase in transverse deformation ensued, enabled by the movement of the fabric plies within the ductile matrix caused by the extension-shear coupling effect characteristic of such laminates. Additionally, and as

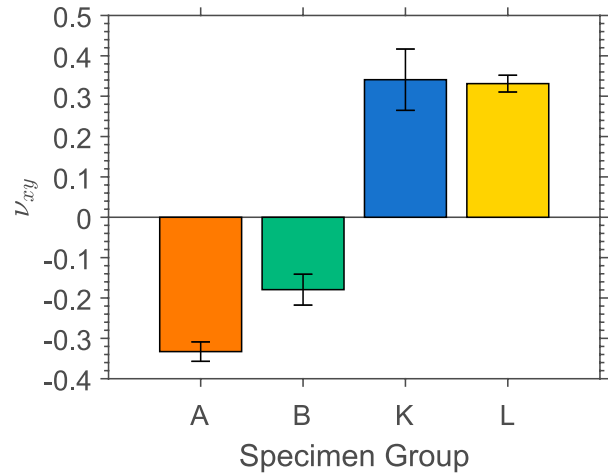


Figure 8. Experimental IP Poisson's ratio, ν_{xy} , bar charts for the A (C/E IP NPR), B (C-G/E IP NPR), K (C/E UD) and L (G/E UD) groups.

expected, IP auxeticity reduces in magnitude with the insertion of G/E plies, due to their low anisotropy.

Figure 9, displaying the stable domain for the $\nu_{xy} - \sigma_x$ relationship of UD groups K and L, evidences an increase of ν_{xy} with increasing σ_x in UD C/E specimens, especially post the 300 MPa mark, with the relationship remaining almost constant in the case of UD G/E specimens (Figure 10).

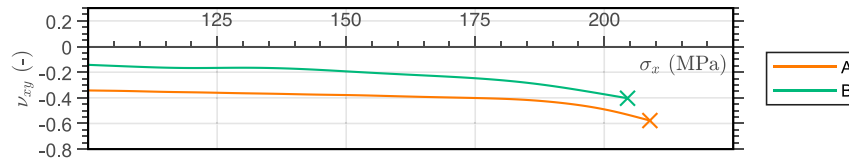


Figure 9. IP Poisson's ratio-stress curves for groups A (C/E IP NPR) and B (C-G/E IP NPR).

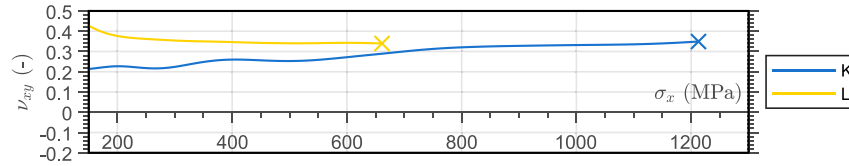


Figure 10. IP Poisson's ratio-stress curves for groups K (C/E UD) and L (G/E UD).

Table 12. Largest IP NPR yielding configurations for T300/8500 C/E and T300+E-glass/8500 C-G/E bidirectional symmetric $[(\theta_1/\theta_2)_n]_s$ laminates.

Material	Lay-up sequence	ν_{xy}	E_x (GPa)	E_y (GPa)	G_{xy} (GPa)
T300/8500	$[(14.0^\circ/63.6^\circ)_n]_s$	-0.412	46.1	22.7	5.69
	$[(0^\circ/14.0^\circ/63.6^\circ/14.0^\circ)_n]_s$	-0.299	81.5	19.5	6.58
T300+E-glass/8500	$[(15.1^\circ/68.6^\circ)_n]_s$	-0.196	36.2	26.9	5.55
	$[(0^\circ/15.1^\circ/68.6^\circ/15.1^\circ)_n]_s$	-0.0958	59.5	21.0	6.08

Given the larger discrepancy between predicted and experimental values in the case of ν_{xy} , when compared to E_x and E_y , one should note that the scattered nature of captured strain data, coupled with the aforementioned selection of a stable sub-domain within a variable set of data for the calculation of the average ν_{xy} , have inevitably interfered with the assertion of experimental values and contributed for this discrepancy.

Further factors that might have affected the results include misalignments along the T300 carbon and E-glass fabric's width, as its weft fixation yarn did not fully compact the UD fiber bundles due to fabric stretching in the transverse direction. Furthermore, the utilised manufacturing techniques - hand lay-up and hot compression moulding - facilitated the development of air bubbles during the resin and hardener mixing stage, which could generate weak points for crack initiation and propagation. Additionally, any misalignments during the fabric cutting, impregnation, and compression stages, as well as during specimen cutting from the hot compressed laminate plates, and specimen fixation for tensile testing, could also contribute to these weak points, and to a misalignment between the direction of tensile load application and the longitudinal direction of the specimens. Although it is true that most of the aforementioned factors have, at worst, induced marginal error in the experimental readings, as they were controlled, the addition of such errors might also aid the explanation for the discrepancies verified.

Alternative design strategies

A key point verified from these results has been the inherent decrease longitudinal tensile strength and elastic modulus in IP auxetic laminates with lay-up sequences which maximise this effect. One consideration that could be taken into account for this problem could be the insertion of 0° plies. Donoghue et al.¹⁸ have worked on an IP auxetic C/E lay-up sequence - $[0^\circ/15^\circ/75^\circ/15^\circ]_s$, with a ν_{xy} of -0.134, and an E_x of 63.4 GPa.

A new analysis was conducted on the developed MATLAB algorithm, with similar lay-up sequences with the inclusion of 0° layers. Elastic properties for the original maximum IP auxeticity C/E and C-G/E lay-ups ($\nu_f = 0.65$) and altered lay-ups are shown in Table 12.²⁹

This inclusion would invariably translate in a decrease of auxetic magnitude, however maintaining auxetic behaviour - residually in the case of the studied C-G/E lay-up sequence. While there is a clear increase in E_x with respect to the maximum NPR sequences, which would improve tensile behaviour, this reduction in ν_{xy} could lead to larger decreases in the associated auxetic enhancements, especially as for the case of low velocity impact resistance and delamination suppression.

As for strength, the inclusion of 0° could promote better distribution of tensile stress, with this orientation angle presenting optimal resistance to this type of mechanical solicitation. Nevertheless, more studies are required, not only on the tensile domain but also under low-velocity impact, to

further study the influence of distinct auxetic sequences on the overall strength of the laminate, in order to obtain the best balance between auxeticity and strength. Moreover, the employment of a fabric with a distinct weft fixation technique might prevent the early formation of local weak points, and avoid premature failure in IP NPR laminates.

Conclusion

In this work, the tensile properties of IP auxetic laminates, under the AuxMMMs umbrella, have been evaluated. Tensile tests, according to the ISO 527-4 standard, using videoextensometry techniques, were performed to UD C/E and G/E specimens, namely T300/8500 and E-glass/8500 laminates, and to C/E and C-G/E IP NPR laminates constituted by the same materials, with lay-up sequences of $[(14^\circ/64^\circ)_4]_s$ and $[(15^\circ/69^\circ)_4]_s$, respectively. The elastic longitudinal and transverse modulus, E_x and E_y , the IP Poisson's ratio, ν_{xy} , and the longitudinal and transverse tensile strength and strain-to-failure, X_f^T , Y_f^T , ϵ_{fx}^T and ϵ_{fy}^T , were evaluated. In the case of the elastic properties, those were compared to analytical predictions based on a previously developed MATLAB algorithm for elastic laminate property calculation.

E_x results correlated well with analytical predictions, especially in the UD cases, with an overestimation of this property for the IP NPR groups, with similar results for E_y . Given the necessary ply orientations in order to achieve maximum auxeticity, a reduction of E_x was verified in the auxetic specimens, when compared to the UD cases. For C/E specimens, E_x was reduced from 141 GPa in the UD case, to 39 GPa in the IP NPR case. The inclusion of G/E plies further reduced E_x amongst the IP NPR cases, as expected given the lower anisotropy of glass fibre, from 39 GPa in C/E specimens to 30 GPa in the hybrid case. This same factor also induced larger ϵ_{fx}^T values.

As for X_f^T , auxeticity led to a large decrease in the capacity of sustaining longitudinal tensile solicitations. For C/E specimens, this property decreased from 1.21 GPa in UD specimens, to 209 MPa in IP NPR specimens. Considering the UD G/E baseline of 660 MPa, hybrid specimens also fared worst with a X_f^T in the region of 204 MPa. Given that the respective failure planes of each group follow the top ply's fibre direction, the required ply orientation angles for maximum auxeticity, coupled with the used fabrics' fibre fixation scheme, promoted the development of weak zones for crack initiation and propagation along fibre direction.

Concerning ν_{xy} results, larger discrepancies between predicted and experimental data were verified, coupled with a overestimation of the magnitude of ν_{xy} in the IP NPR cases. Auxeticity was experimentally observed, with a ν_{xy} of -0.333 and -0.180 for the C/E and C-G/E

tested groups, respectively. When comparing these values to UD C/E and G/E readings, with averages at 0.341 and 0.331, respectively, it becomes evident that auxeticity is a structural property that arises, mainly, from the lay-up configuration of a given laminates. Even so, material anisotropy still plays a key role for the development and maximization of auxeticity, as evidenced by the reduction in IP NPR magnitude from the C/E to the C-G/E group, due to the inclusion of less anisotropic glass fibres.

From this study, it is evident that the lay-up sequences required for maximisation of IP auxeticity lead to significant decreases of stiffness and strength from the UD case. An alternative design was analysed analytically, with the insertion of 0° plies in IP NPR specimens. Analytical elastic results show an increase of E_x from 46 GPa to 81 GPa in C/E, and 36 GPa to 59 GPa C-G/E lay-up sequences, between the maximum NPR configurations and the alternative. This comes with a decrease of auxetic capacity - from -0.4 to -0.3 in the C/E case, and from -0.2 to -0.1 in the hybrid sequences.

Thus, IP auxeticity has been verified experimentally for C/E and C-G/E laminates. The maximisation of NPR is accompanied by reductions in stiffness and strength, which can be improved with the utilisation of alternative auxetic lay-up sequences. Yet, more research on novel auxetic sequences is necessary - not restricted to bidirectional lay-up sequences - to manage an equilibrium between the stiffness and strength, and auxetic enhancements, especially regarding LVI enhancements, with the final intent of the widespread application of these metamaterials in components for improved LVI resistance and reduced delamination propagation.

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Data availability statement

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

Notes

1. Subscripts n and S refer to, respectively, a number of repetitions of a given set of angles, and laminate symmetry.
2. For hybrid groups, the following assumption was employed:

$$\mathbf{v}_{fc} = \mathbf{v}_{fg} = \mathbf{v}_{fl}.$$

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