Mechanical Performance of Long-fibre Reinforced Polymer Composites by 3D Printing

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Research

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Abstract

Additive Manufacturing (AM), also known as 3D Printing, has been around for more than 2 decades and has recently gained importance for use in direct manufacturing. The quantified physical properties of materials are required by design engineers to inform and validate their designs, and this is no less true for AM that it is for traditional manufacturing methods. Recent innovation in AM has seen the emergence of long-fibre composite AM technologies, such as the Mark Two (Markforged Inc, USA) system, enabling the manufacture of thermoplastic polymer composites with long-fibre reinforcement. To date though, the mechanical response of the materials with respect to build parameter variation is little understood.

In this project, selected mechanical properties (ultimate tensile strength – UTS and flexural modulus) of samples processed using the Mark Two printer were studied. The effect of the reinforcement type (Carbon, Kevlar®, and HSHT glass), amount of reinforcement, reinforcement lay-up orientation, and the base matrix material (Onyx and polyamide) on these properties were assessed using accepted standard test methods.

For Onyx, the UTS and Flexural Modulus was improved by a maximum of 244 ± 10 MPa (1228 ± 19%) and 14.2 ± 0.3 GPa (1114 ± 6%) (Carbon), by 143 ± 1 MPa (721 ± 18%) and 7.1 ± 0.3 GPa (560 ± 6%) (Kevlar®) and 209 ± 4 MPa (1049 ± 19%) and 6.0 ± 0.1 GPa (469 ± 6%) (HSHT glass).

For Nylon the UTS and Flexural Modulus was improved by 235 ± 4 MPa (1431 ± 56%) and 14.1 ± 0.2 GPa (1924 ± 5%) (Carbon), 143 ± 3 MPa (867 ± 56%) and 6.79 ± 0.08 GPa (927 ± 5%) (Kevlar®) and 204 ± 2 MPa (1250 ± 55%) and 5.73 ± 0.09 GPa (782 ± 5%) (HSHT glass).

A regression and ANOVA analysis for UTS indicated that the number of layers of reinforcement had the largest impact on UTS ($F = 11{,}483$ $P < 0.005$), with the second most important parameter being the type of reinforcement ($F = 855$ $P < 0.005$). The parameter effects for all four parameters were significant ($P \leq 0.05$). For the Flexural Modulus, the number of layers of reinforcement was again the most significant parameter ($F = 2733$ $P < 0.005$), with the second most important parameter again being the type of reinforcement ($F = 1339$ $P < 0.005$). Again, the parameter effects for all four parameters were significant ($P \leq 0.05$), although the influence of base material had much less significant effect on determining the Flexural Modulus than it did in controlling UTS.

1. Introduction

Developments in composites compositions, and understanding the design and manufacturing using Additive Manufacturing (AM) is an important research field today [1], which can be seen from Wohler's Report 2016, that production of end use parts represented 51% of the worldwide market using AM, with Material Extrusion being the most widely used method [2]; the reason being high demand of these materials in the aerospace and automobile sectors due to them being light-weight, having high static strength, good fatigue resistance and damage tolerance [3], [4]. One of the most important applications is in light-weighting in the aerospace sector, one widely recognised being the main fuselage and the wings of the Boeing 787 being composite, and in total 50% of the material used in the aircraft is advanced composites. This reduces the maintenance requirements and cost, and increases the total reliability of the airplane, reducing the weight by 20% [5]. In the automotive industry, the fuel efficiency can be increased by light-weighing cars, with the use of thermoplastic or thermoset composites instead of steel. A weight reduction of 55% was achieved for a conventional 9 m bus [6]. The energy absorption for some thermoplastic composites can be 7–8 times that of traditional steel [7], offering opportunities for improved crash protection.

There is a growing interest in the use of AM for the manufacture of composite components. The benefits of AM, in offering flexibility in design (opening up the pathway to light-weight internal structuring and for part consolidation [8]), and tool-less manufacture (removing the cost burden and extensive lead-time for tooling, especially for low volume manufacture as within the aerospace and niche vehicle land-transport sectors [9]). These capabilities make it a very attractive proposition for these sectors, but uptake has been limited to date due to the poor mechanical properties that are obtained from the polymers [10], with, until relatively recently, no capability for improving mechanical properties through their reinforcement using long or continuous fibres.

Recently, long fibre reinforcement of composites has been developed to a commercial offering, provided by, for example, MarkForged Inc. The technology, based on the Material Extrusion AM technology, where a filament of polymer is melted and extruded through a nozzle onto a planar platform, with addition of multiple layers forming the component. A continuous reinforcing filament is deposited onto, and embedded into, the deposited polymer tracks, thus allowing long-fibre reinforcement of the polymer matrix [11].

The right balance of matrix and reinforcement materials in a polymer composites result in optimal tensile strength and stiffness for specific applications [12]. Also, these mechanical properties are affected by the various build parameters during Additive Manufacturing. Hence the selection of the right balance of composite components and optimal build parameters are equally important. Known mechanical properties are important to understand the reliability and the future performance of the part that is designed and since the MarkForged technology is relatively new, there is little available mechanical performance data available. The aim of this paper is to characterise the mechanical performance of two common matrix materials employed in Material Extrusion (polyamide (PA) and Onxy (PA-carbon fibre composite) thermoplastics) with a range of fibre reinforcements (High Strength High Temperature Glass Fibre – HSHT (GF), Kevlar® Fibre (KF) - poly paraphenylene terephthalamide, and Carbon Fibre (CF), and processed using a range of build parameters (number of reinforcement layers and fibre-placement orientation). We aim to identify, through a statistical analysis of the material performance, the role of each material and build parameter choice on the mechanical response of the material. This will provide product designers with the tools to enable them to utilise this technology in designing products to satisfy engineering requirements.

2. Additive Manufacture Of Thermoplastic Composite Components

Additive Manufacturing (AM) is widely used for the fabrication of polymer components ranging from prototypes to end-use parts [13]. A wide range of AM technologies have been developed including Vat Polymerisation [14], Binder Jetting [15], Material Jetting [16] and Material Extrusion [17]. The latter is widely used due to its ease of use, low cost and ubiquity within the market-place [18]. The Material Extrusion process consists of a thermoplastic filament feed into a heated nozzle, where it is melted and deposited onto planar platform under CNC (Computer Numerical Control). After the manufacture of one layer of the component, the platform lowers (or the nozzle is raised) by one-layer thickness (typically 0.05–0.2 mm) and the next layer is deposited. This is continued until the product is complete.

Non-reinforced thermoplastics used in this process suffer from poor mechanical properties [10], which as limited the widespread uptake of this technology for end-use products. Some attempt has been made to improve properties, e.g through the use of chopped fibre reinforcement, such as glass fibre and polypropylene (PP) fibre in PP matrix, showing 30 and 40% improvement in UTS compared to pure PP [19], and 5 wt% of either vapour grown carbon fibres (VGCFs) and single wall carbon nanotubes (SWNTs) in an acrylonitrile butadiene styrene (ABS) providing a 18% and 31% improvement in UTS [20]. The larger challenge of incorporating continuous or long fibre reinforcement into AM polymer composites offers the opportunity for significantly larger improvements in mechanical properties. This has been achieved by a number of researchers, namely, Matsuzaki et al. [21], developed in-nozzle impregnation of carbon and other fibres in polylactic acid (PLA), with large increases in UTS and flexural modulus observed. Addition of reinforcing fibres into the deposited polymer layers was an approach taken by Mori et al. [22], with the embedding of Kevlar® fibres into a nylon matrix using a desktop Material Extrusion system, improving strength and fatigue properties. Van Der Klift et al. [23] studied the mechanical behaviour of 6 layers of carbon fibre embedded in a polyamide matrix using a commercial Mark One AM system (Markforged Inc, USA), observing a 9x increase in UTS over the unreinforced material, with similar studies by Dickson et al. [12] extending the study to the effect of Kevlar® reinforcement, with up to 6.3x increase in UTS and flexural strength observed.

There is thus a growing body of work in observing the effect of continuous fibre reinforcement of AM thermoplastic composites, providing evidence of useful and significant increases in mechanical properties. These studies though are, to date, lacking any use of experimental design accompanied by statistical analysis to elucidate the individual effects of material choice and build parameters on the mechanical response of the materials. This paper aims to provide product designers, and users of commercial continuous fibre AM technology, with a knowledge base capturing the impact and statistical significance of the choice of base material, the reinforcement material, and some key build parameters; allowing them to make informed decisions in the choice of materials and parameters to meet their design needs.

3. Research Methodology

3.1. Sample Manufacture

3.1.1. Materials

Mechanical test samples were manufactured using a Mark Two Material Extrusion system (Markforged Inc, USA). The base materials employed were nylon, a proprietary polyamide composition from Markforged) and Onyx, a proprietary short carbon fibre reinforced polyamide composite from MarkForged. Both filaments were 1.75 mm diameter, and were kept in a dry box prior to, and during use.

The reinforcing filaments used were glass Fibre (GF) – 0.3 mm bundles, carbon Fibre (CF) – 0.35 mm bundles, and Kevlar® Fibre (KF) – 0.3 mm bundles, all supplied by MarkForged Inc. Tensile and flexural test specimens were manufactured, based on standard designs; ASTM D3039 [24] for tensile samples and ASTM D7264 [25] for flexural samples. ASTM D3039 was chosen over an ISO standard as it allows for easier set-up to avoid flexure of the sample under test [26]. ASTM 7264 (four-point bend testing) was preferred over three-point bend testing as it has been shown that the error in the flexural modulus from 3-point is 5% higher than 4-point [27]. The specifications of the samples are given in Table 1. ASTM D3039 requires the addition of tabs at the sample ends to avoid damage due to test grips. The standard allows for the printing of the tabs during sample manufacture, as used by Giannakis [28], however, the more widely accepted method of using adhesion of tabs was employed to reduce AM costs and time. Tabs were applied following ASTM D3039, using NEMA standards Grade G-10/FR4 composite (PAR Group Ltd, UK), 30 mm tab length and a bevel angle of 90^{o}, also recommended by Hodgkinson [26]. The tabs were adhesively bonded to the specimens using a heat-cured epoxy VTA 260 (Cytec Industrial Materials (Derby) Ltd, UK). The samples were vacuum bagged and heated at 65^{o}C for 16hrs to effect a cure.

Table 1
Tensile and Flexural Test Sample Specifications.

Test Method	Shape	Length (mm)	Width (mm)	Thickness (mm)
Tensile ASTM D3039	Rectangular	175	12.7	3.2
Flexural ASTM 7264	Rectangular	150	13	4

3.1.2. Parameter Selection

A number of the available build parameters defining the structure of the samples (Fig. 1) were set at constant levels. These were ‘wall layers’ – the number of layers of fibre reinforcement in the walls, ‘floor layers’ – the number of reinforcement layers in the floor, and ‘ceiling layers - the number of

The parameters selected for variable analysis were base material, reinforcement material, number of reinforcement layers and reinforcement orientation. Base materials were Nylon and Onyx (Markforged Inc, USA), and reinforcement materials were GF, CF and KF (MarkForged Inc, USA). Two values for number of reinforcement layers were selected (4 and 12), which are at allowable extremes for both sample thicknesses.

The reinforcement orientation (fibre layup angle) also affects the mechanical properties of the composites [29]. A unidirectional angle orientation has higher strength but only in the direction of the fibre. However, to allow wider application in products where multi-directional strength is required, a bi-directional lay-up is desirable [32], and (0^0,45^0) and (0^0,90^0) were selected.

3.1.3. Sample Manufacture

Samples were manufactured using a Mark Two AM system (MarkForged Inc, USA) using the materials identified in 3.1.1 and parameters identified in 3.1.2. A standard full-factorial design of experiment was employed to allow statistical variation of parameters to be assessed. A multilevel design was used, with 4 factors (three 2-level and one 3-level) and 5 replicates. A summary of the DoE structure is given in Table 2. Samples were also manufactured for un-reinforced Nylon and Onxy (5 of each) to provide baseline performance comparison.

Table 2
Summary of Parameters Employed and Levels Set for Sample Manufacture.

Parameter	Number of Levels	Parameter Values
Matrix Material (M)	2	Nylon, Onyx
Reinforcement Material (R)	3	Glass Fibre, Carbon Fibre, Kevlar Fibre
Number of Fibre Layers (RL)	2	4, 12
Fibre Orientation (F)	2	(0^0,45^0), (0^0,90^0)

3.1.4. Sample Evaluation

For both tensile and flexural testing, testing was performed at 20-22^{0}C. Extension was measured using an Instron 50 mm gauge length extensometer (Instron, USA).

3.1.4.1. Tensile Test Measurement

Tensile testing was performed using an Instron 3367 tensile testing rig (Instron, USA), with a 30kN load cell with a cross-head speed of 2 mm/min (as per ASTM D3390). An extensometer (Instron, USA) with 50 mm gauge length was used. The dimensions of each sample were taken at three places using a digital micrometre screw gauge with measurement accuracy ± 0.001 mm.

3.1.4.2. Flexural Test Measurement

4-point flexural testing was performed using an Instron 5800R (Instron, USA), with a 100kN load cell. A cross-head speed of 1 mm/min was employed as per ASTM 7264. The span length was set to 128 mm, corresponding to a 32:1 span to thickness ratio as per the standard. Flexural modulus was calculated for the slope of the stress-strain curve at 0.15% strain level.

4. Results And Analysis

The data from the mechanical testing was analysed within a statistical analysis software, Minitab v19 (Minitab LLC, USA). An Analysis of Variance was performed to provide the size of each parameter effect (F-Value) and the significance of each parameter effect (P-Value). The results of the statistical analysis for the Ultimate Tensile Strength (UTS) and Flexural Modulus (E) are given in Table 3 (UTS) and Table 4 (E).

Table 3
ANOVA Results for Main Parameters and All Interactions for UTS.

ANOVA Analysis Results for UTS					
Parameter	**F-Value**	**P-Value**	**Parameter**	**F-Value**	**P-Value**
Main Parameters			3-Way Interactions		
Matrix Material (M)	169.89	0.000	M*R*L	9.30	0.000
Reinforcement Material (R)	855.22	0.000	M*R*O	3.86	0.024
Number of Fibre Layers (L)	11,483	0.000	M*L*O	19.00	0.000
Fibre Orientation (O)	8.25	0.005	R*L*O	0.75	0.473
2-Way Interactions			4-Way Interaction		
M*R	9.42	0.000	M*R*L*O	10.90	0.000
M*L	6.87	0.010			
M*O	12.56	0.001			
R*L	297.61	0.000			
R*O	1.52	0.223			
L*O	2.60	0.110			

Table 4
ANOVA Results for Main Parameters and All Interactions for E.

ANOVA Analysis Results for E					
Parameter	**F-Value**	**P-Value**	**Parameter**	**F-Value**	**P-Value**
Main Parameters			3-Way Interactions		
Matrix Material (M)	6.90	0.010	M*R*L	33.30	0.000
Reinforcement Material (R)	1,338	0.000	M*R*O	137.46	0.000
Number of Fibre Layers (L)	2,733	0.000	M*L*O	55.09	0.000
Fibre Orientation (O)	96.83	0.000	R*L*O	8.66	0.000
2-Way Interactions			4-Way Interaction		
M*R	114.25	0.000	M*R*L*O	99.16	0.000
M*L	17.63	0.000			
M*O	68.73	0.000			
R*L	76.28	0.000			
R*O	64.96	0.000			
L*O	37.52	0.000			

The Pareto charts for the standardised parameter effects for UTS and E are given in Fig. 3 and Fig. 4.

Parameters significant at 95% ($\alpha < 0.05$) are those with a Standardised Effect > than the red line. The red line is drawn at t, where t is the $(1 - \alpha / 2)$ quantile of a t-distribution with degrees of freedom equal to the degrees of freedom for the error term (2.0 for UTS and 1.98 for E). The Main Effects Plots for each parameter and level are given in Fig. 5 (UTS) and Fig. 6 (E). These indicate the average change in the UTS and E when selecting a particular parameter level. Tables 5 and 6 show the calculated differential mean UTS values (as a % of the global average UTS (dotted line on Fig. 5)) and mean E values (as a % of the global average E (dotted line on Fig. 6)) for each of the parameter levels.

Table 5
Main Effect Changes on Average UTS.

	Parameter			
Level	Matrix	Reinforcement	Layers	Orientation
1	-5.68%	-0.14%	-46.52%	-1.23%
2	11.66%	22.06%	46.56%	1.27%
3		-22.94%		

Table 6
Main Effect Changes on Average E.

	Parameter			
Level	Matrix	Reinforcement	Layers	Orientation
1	-1.55%	-0.12%	-30.76%	-5.78%
2	1.55%	42.75%	30.76%	5.80%
3		-16.98%		

The Cost Ratio ($/MPa) for UTS, and UTS for each of the 24 composites and for the un-reinforced Nylon and Onyx (average of 5 samples for each) is given in Fig. 7. The Cost Ratio ($/GPa for E, and E for each of the 24 composites and for the un-reinforced Nylon and Onyx (average of 5 samples for each) is given in Fig. 8. The cost for manufacture used to calculate the Cost Ratio values was calculated using the material usage (matrix and reinforcement) recorded from the Mark Two printer after each build (and divided by 5 to obtain cost / part).

5. Discussion

As can be seen from Tables 3 and 4 and Figs. 3 and 4, for both UTS and E, all four main parameters are statistically significant (Standard Effect is higher than the significance line for 95% significance) and can control the mechanical response of the material, although the number of layers is highly significant for both UTS and E, and is significantly more important than any other parameter. It is surprising that the type of reinforcement has such a small effect on the mechanical response, with the Standardised Effect on UTS for 'reinforcement' being only 27% of that for 'layers' (Fig. 3), although for E, the effect is more significant, being 70% of that for 'layers' (Fig. 4). The type of matrix material has been shown to have very little effect on the mechanical response, with the Standardised Effect for 'matrix' being only 12% of that for 'layers' for UTS (Fig. 3) and only 5% of that for 'layers' for E (Fig. 5). Also, for E, the 'matrix' parameter is only just significant (2.63) compared to the significance limit of 1.98. Thus, lower-cost, and more abundant Nylon matrix material offers similar performance to the more expensive Onyx. 'Orientation' has a standardized effect of only 3% for UTS and 19% for E compared to those for 'layers'.

The selection of parameter levels for main parameters can be informed from the Main Effects Plots (Figs. 5 and 6 and Tables 5 and 6). These indicate the change in observed average (over all samples) mechanical response as a result in change in parameter level. From Figs. 5 and 6 and Tables 5 and 6 it is clearly evident that the results for UTS and E follow similar, but not identical trends. For 'matrix' parameter, both UTS and E, selecting Onxy over Nylon does provide a small increase in both UTS and E, but, this is only (UTS) from 5.58% below global mean to 11.66% above (Table 5) and (E) from − 1.55% below global mean to 1.55% above (Table 6). Thus, optimal properties are achieved by selecting Onyx over Nylon as matrix material, although, as discussed later, the improvements in mechanical response may bot outweigh the extra cost incurred.

For ‘reinforcement’ parameter, there is a large effect in moving from GF to CF, with large increases in both UTS (from 0.14% below global mean to 22.06% above – Fig. 4 and Table 5) and E (from 0.12% below global mean to 42.75% above – Fig. 5 and Table 6). There is a nearly equally sized decrease in properties for both UTS and E when selecting KF, shifting to 22.94% below global mean (UTS) and 16.98% below global mean (E). Thus, optimal properties are obtained by selecting CF as reinforcement material.

As discussed initially above, the ‘layers’ parameter has the largest influence over the mechanical properties. From the Main Effect plots for UTS and E (Figs. 5 and 6), moving from 4 layers to 12 layers provides a improvement in UTS from 46.52% below global mean to 46.56% above global mean; the same change results in raising E from 30.76% below global mean to 30.76% above global mean. Thus, optimal properties are obtained by using a higher number of reinforcement layers, and, as we see later, is an affordable choice.

Fibre orientation, within the bounds of these trials (0,45 and 0,90 bi-directional orientations) has very little impact on either UTS (2.87 at significance limit of 2.0) (Fig. 3) or E (9.84 at significance limit of 1.98). The Main Effect plots also demonstrate the marginal improvement in moving from a (0,45) pattern to a (0,90) pattern, with UTS increasing from 1.23% below global mean to 1.27% above global mean (Table 5), and E increasing from 5.78% below global mean to 5.80% above global mean (Table 6). This small effect may be due to the similarity between the two lay-up patterns. Higher performance was achieved by Klift et al [23], achieving 400 MPa ($\sigma = 20.35$) UTS for Nylon-Carbon samples, using a concentric ring lay-up, with our Nylon-CF only achieving 249 ± 6 MPa. Although the results are not directly comparable as Klift et al. used an increased number of reinforcement layers of 16, compared to 12 in our research. It is clear though from this research that a (0,90) pattern does help to optimise the UTS and E and has no significant effect on the cost (as we see later).

It can be deduced from the analysis of cost verses strength (Fig. 7) and stiffness (Fig. 8) that the lowest cost to strength ratio (most desirable) is achieved using a GF reinforced Nylon with 12 layers and (0,90) lay-up, at 0.0221 ± 0.0002 $\$MPa^{-1}$, and achieving 220 ± 2 MPa UTS (79 ± 1% of highest UTS, achieved using CF reinforced Onyx with 12 layers and (0,90) lay-up. The equivalent material using (0,45) only achieves a UTS of 187 ± 4 MPa (67 ± 1% of highest UTS) at a cost to strength ratio of 0.0261 ± 0.0005 $\$MPa^{-1}$. The highest performing composite, 278 ± 4 MPa (CF reinforced Onyx with 12 layers and (0,90) lay-up) has a cost to strength ratio of 0.0303 ± 0.0004 $\$MPa^{-1}$, 37 ± 2% higher cost than the optimum cost to strength ratio material. Thus, for a 21 ± 1% increase in strength, a 37 ± 2% increase in cost is incurred, making the most cost-effective material option highly attractive for all but the most demanding applications.

The stiffest material is CF reinforced Onyx with 12 layers and (0,90) (15.5 ± 0.3 GPa), and is 2nd most cost-effective material (0.49 ± 0.06 $\$GPa^{-1}$) (Fig. 8). The most cost-effective material is GF reinforced Nylon with 12 layers and (0,45) (0.40 ± 0.02 $\$GPa^{-1}$), which is 20 ± 3% lower cost but only retains 39 ± 2% of the stiffness of the stiffest material. It is therefore only practical to use this most cost-effective material where high stiffness is not a design requirement. Only three materials have E > 10 GPa, and these are all CF reinforced with 12 layers. It is therefore practical to use the stiffest material (CF reinforced Onyx with 12 layers and (0,90)) for all but the most cost-sensitive applications. KF does not provide any technical advantage over CF and is also not competitive economically.

6. Conclusions

The mechanical capabilities of a continuous fibre thermoplastic composite AM technology (Mark Two, MarkForged Inc, USA) has explored for all the continuous-fibre reinforcement options available (glass, carbon and Kevlar®) and have demonstrated that it has the capability to engage in engineering applications provided the correct choice of process (printing) parameters and materials is made.

The effect of the key process parameters of: matrix polymer, reinforcement fibre, level of reinforcement and reinforcement lay-up, upon the strength (UTS) and stiffness (E) were evaluated using a DoE and ANOVA methodology, per approved ASTM standards. The following conclusions can be made:

1. 'Layers' and 'Reinforcement' play a very significant role in determining both tensile and flexural properties, with Layers being significantly more important in determining UTS than any other parameter (73% higher standardized effect than 'reinforcement').
2. The fibre layup angle and matrix material have a minor effect on the mechanical properties. 'Matrix' having a standardized effect only 12% that of 'layers' for UTS and 5% that of layers for E; 'orientation' having a standardized effect only 3% that of 'layers' for UTS and 19% that of layers for E.
3. Optimal properties are obtained by selecting CF as reinforcement material, using a higher number of reinforcement layers (demonstrated to be an affordable choice) and by selecting Onyx over Nylon as matrix material, although the improvements in mechanical response may not outweigh the extra cost incurred.
4. For UTS, the size of effect of 'reinforcement' was found to be CF > GF > KF; while for E it was CF > KF > GF.
5. GF can improve the tensile and flexural modulus of Nylon by 1340±293% and 876±52% and of Onyx by 1390±234% and 569±37%.
6. CF can improve the tensile and flexural modulus of Nylon by 1472±187% and 2024±107% and of Onyx by 1400±153% and 1214±81%.
7. KF can improve the tensile and flexural modulus of Nylon by 960±243% and 1027±53% and of Onyx by 810±83% and 627±37%.
8. The highest UTS material is CF reinforced Onyx with 12 layers and (0,90) (278 ± 8 MPa).
9. The stiffest material is CF reinforced Onyx with 12 layers and (0,90) (15.5 ± 0.3 GPa).
10. Best cost-strength ratio is obtained using a GF reinforced Nylon with 12 layers and (0,90) lay-up, achieving 220 ± 2 MPa UTS (79 ± 1% of highest UTS).
11. Best cost-stiffness ratio is obtained using a GF reinforced Nylon with 12 layers and (0,45), achieving 6.03 ± 0.1 GPa (39 ± 2% of the stiffest material).

List Of Abbreviations

ABS Acrylonitrile Butadiene Styrene

AM Additive Manufacturing

ANOVA Analysis of Variance

CF Carbon Fibre

CNC Computer Numerical Control

E Flexural Modulus

GF Glass Fibre

GPa Giga Pascals

KF Kevlar® Fibre

kN Kilo Newton

mm Millimetres

MPa Mega Pascals

PLA Polylactic Acid

PP Polypropylene

SWNTs Single Wall Carbon Nanotubes

UTS Ultimate Tensile Strength

VGCFs Vapour Grown Carbon Fibres

Declarations

Availability of data and materials

All data is stored on a secure server at the WMG, University of Warwick.

Competing interests

None

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WMG, University of Warwick.

Authors' contributions

F Dantas – Performed research and developed report for MSc. Data analysis.

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Figures

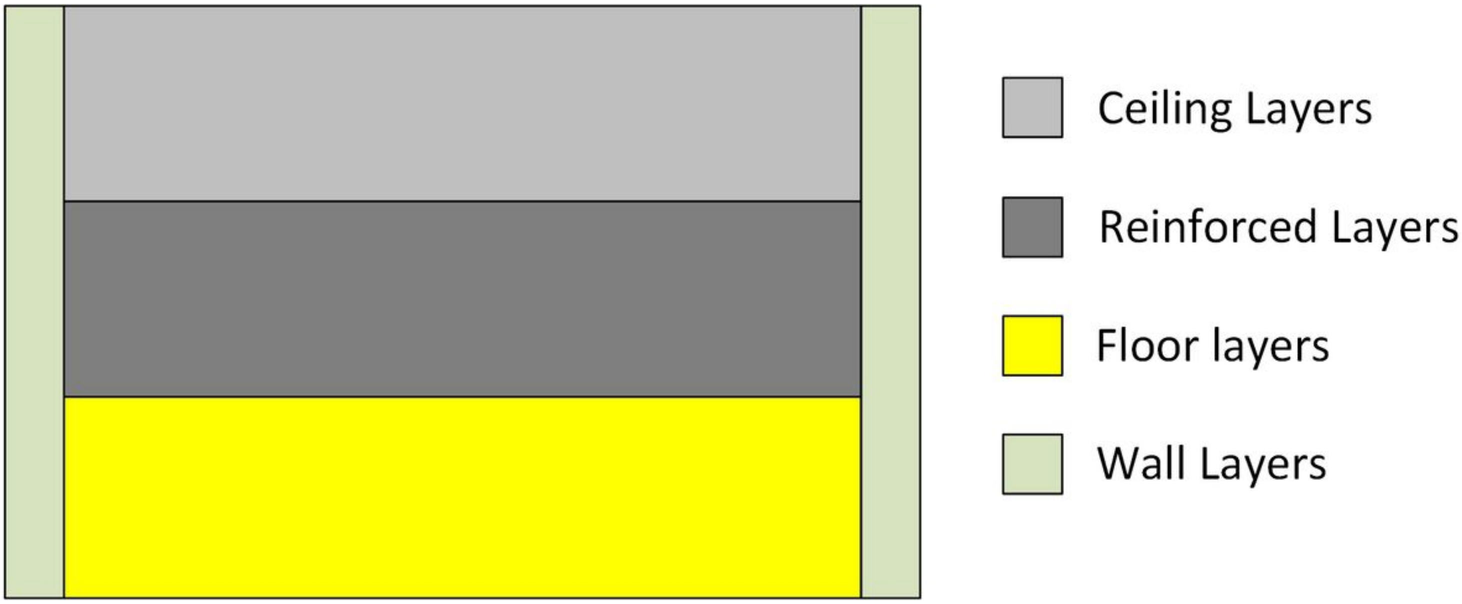

Figure 1

Schematic representation of the structure of a sample deposited using the Mark Two Printer.

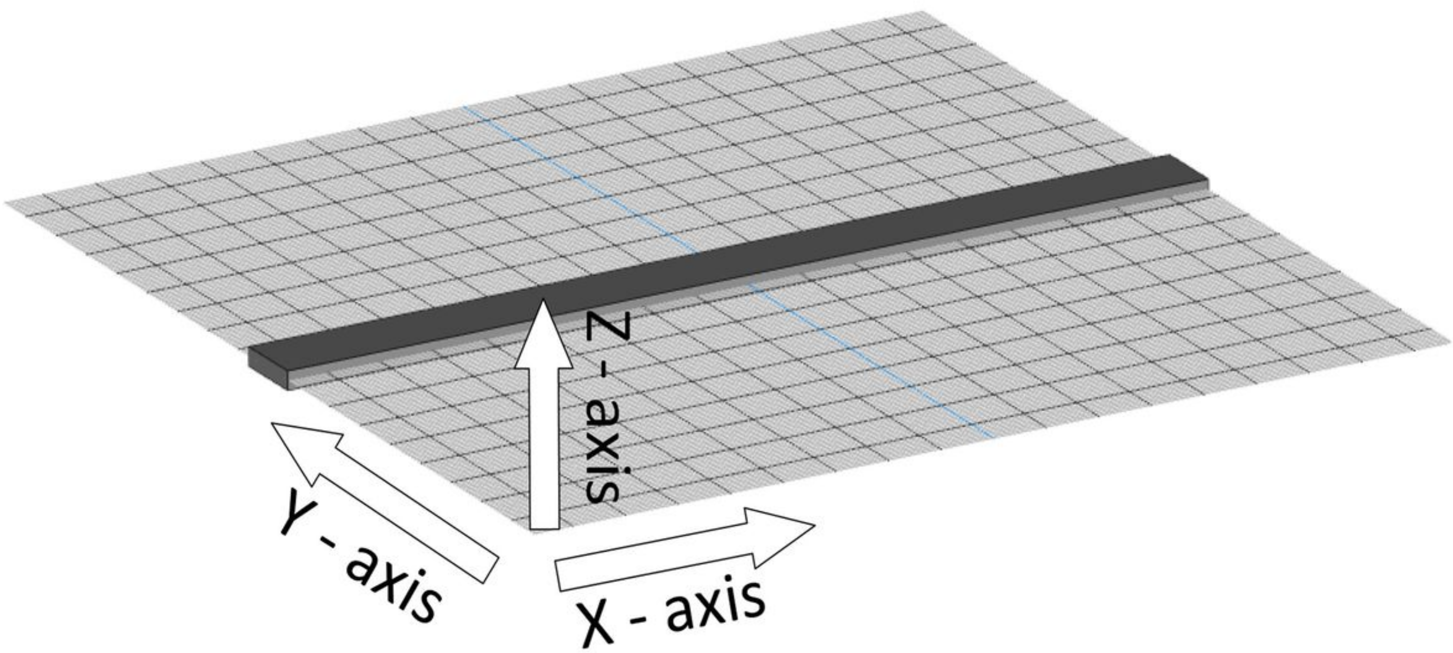

Figure 2

Build Orientation for Mechanical Test Samples

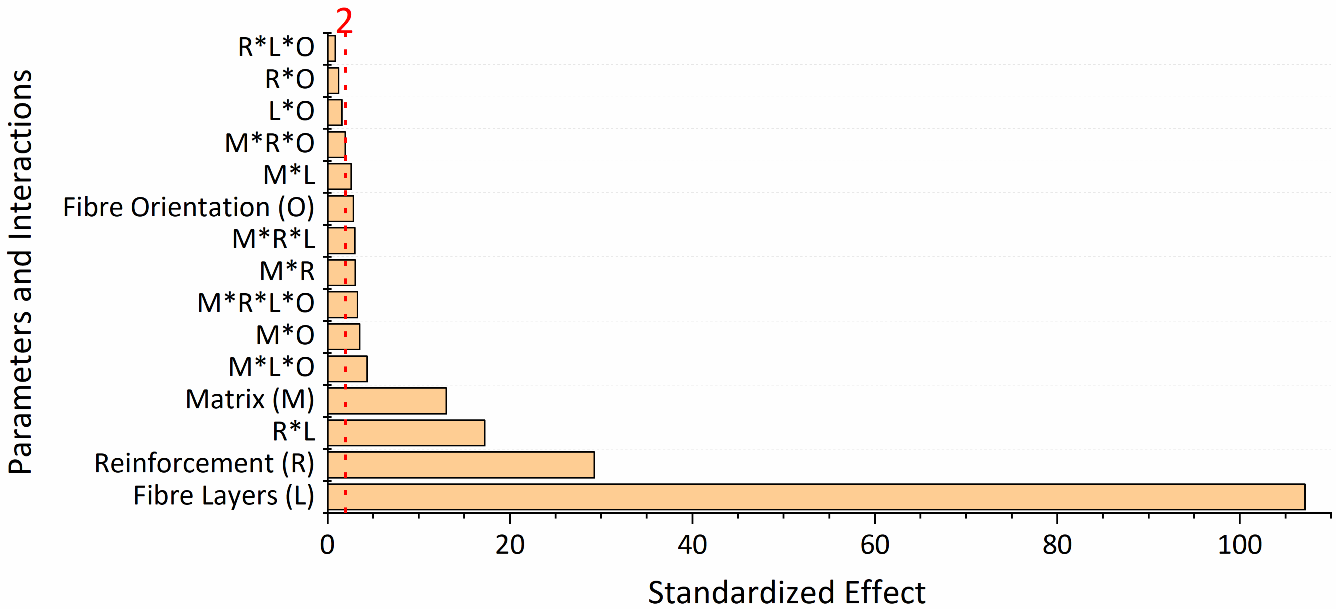

Figure 3

Pareto Chart for Standardized Parameter Effects for UTS (α=0.05).

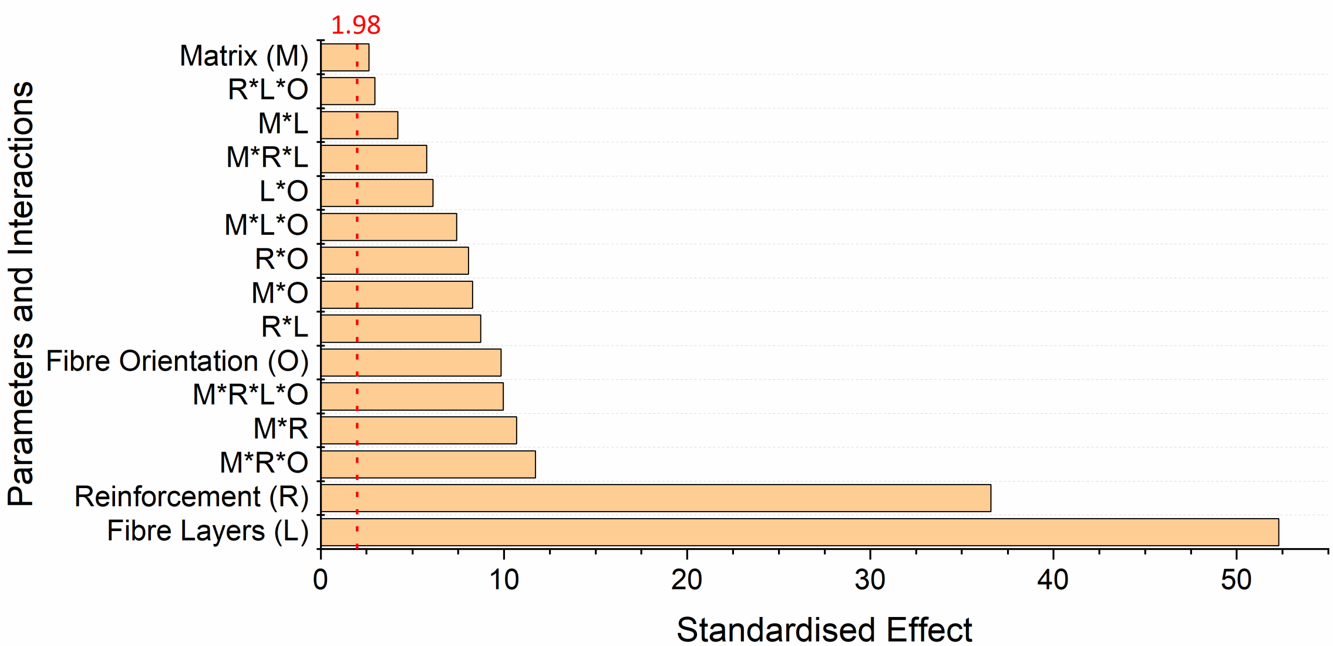

Figure 4

Pareto Chart for Standardized Parameter Effects for E (α=0.05).

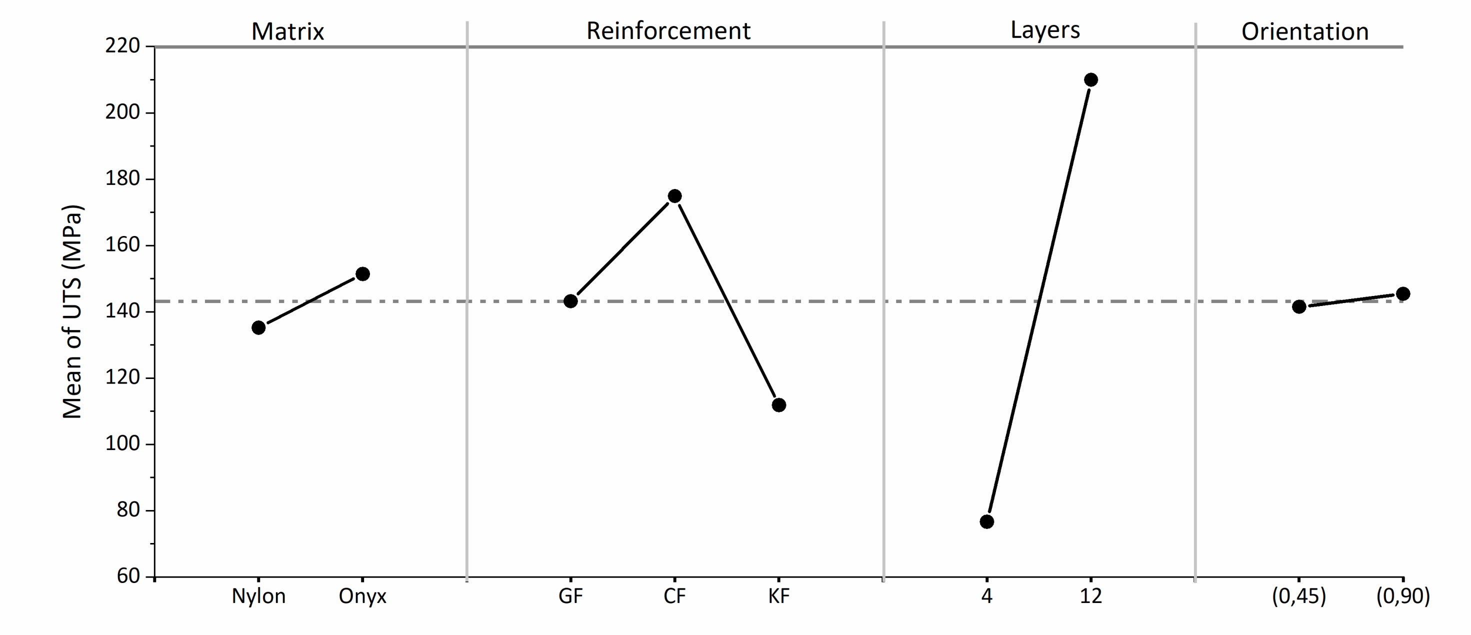

Figure 5

Main Effect Plot for UTS.

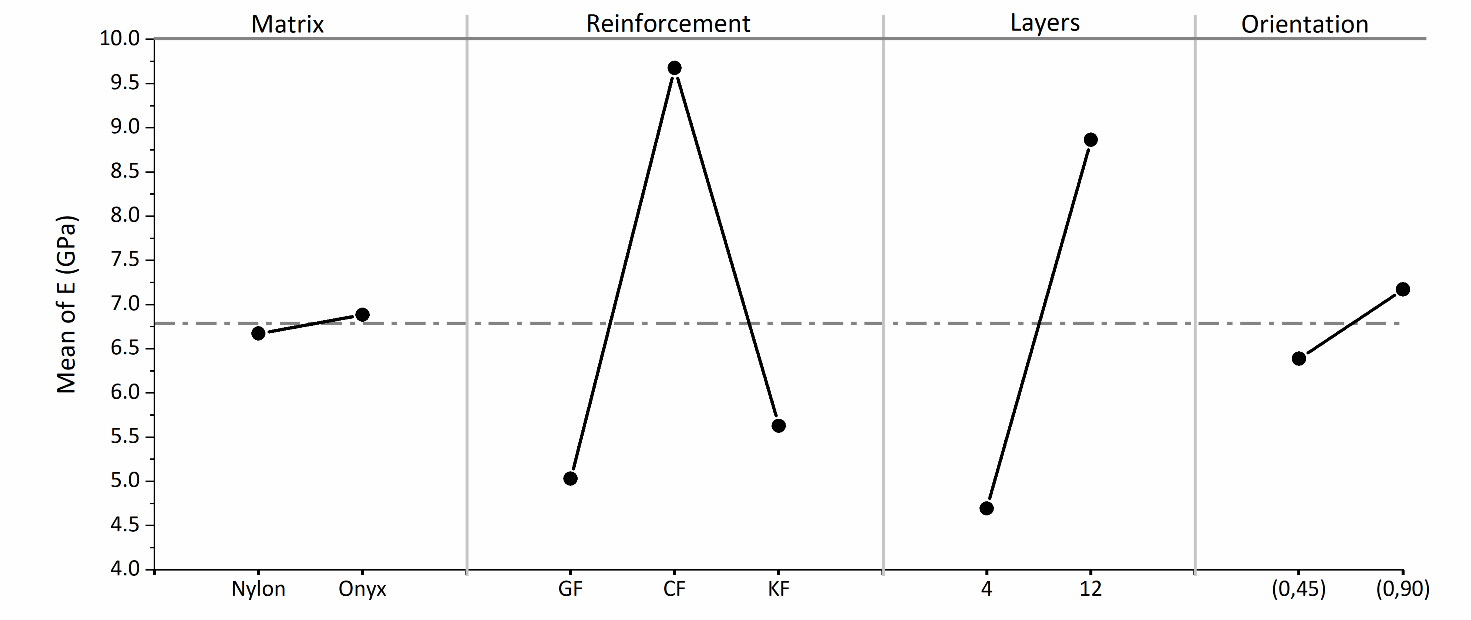

Figure 6

Main Effect Plot for E.

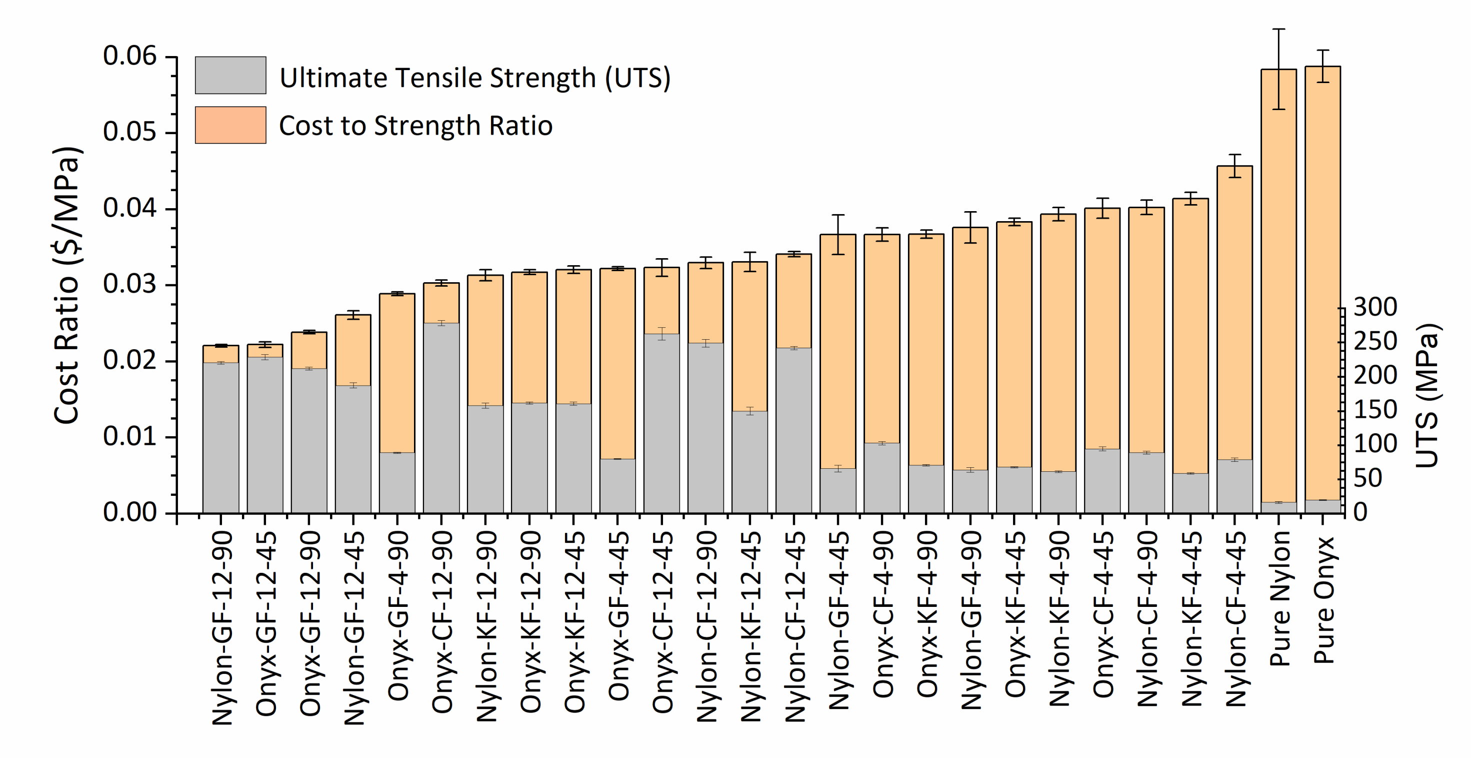

Figure 7

Cost Ratio ($/MPa) and UTS for Composites and Un-reinforced Materials.

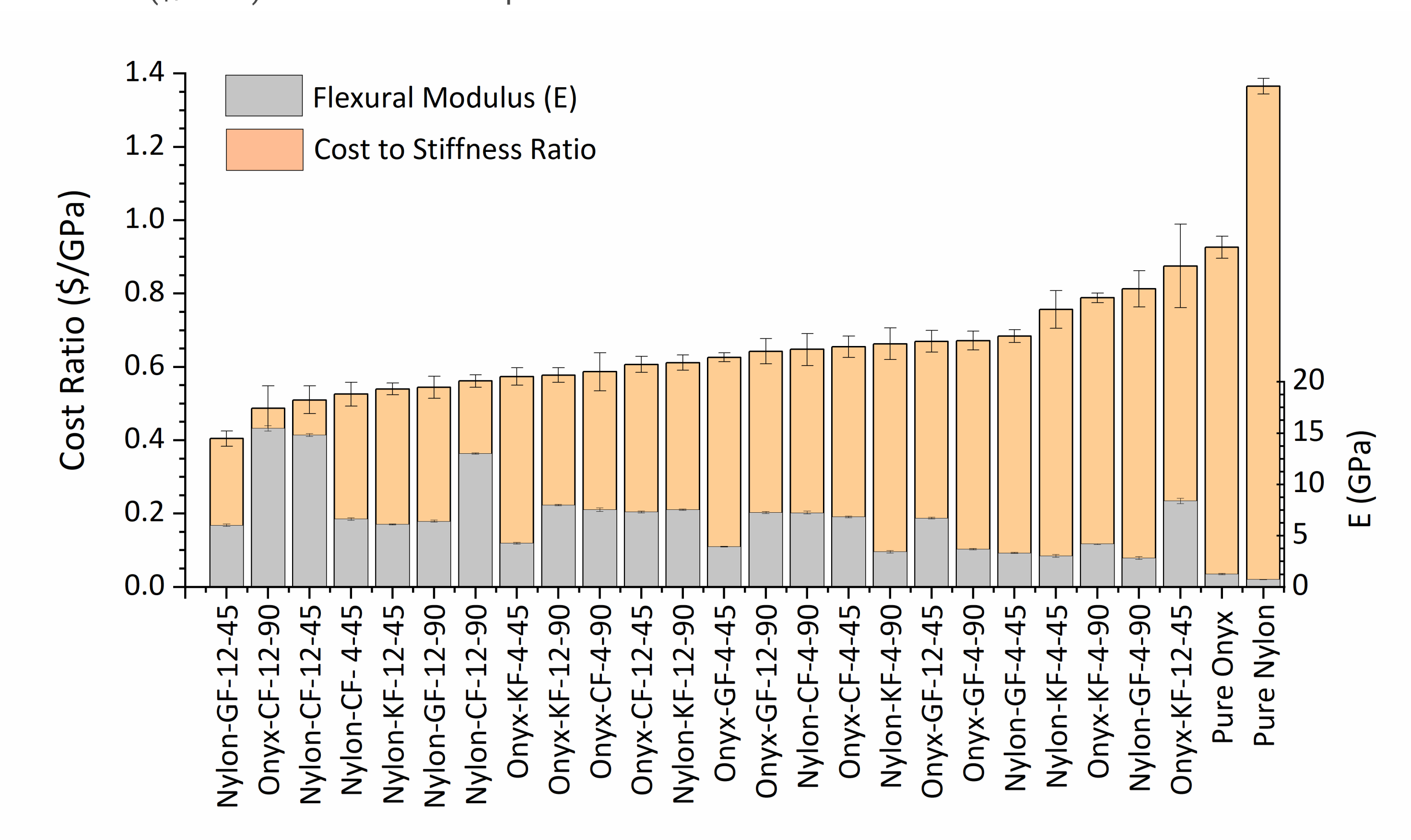

Figure 8

Cost Ratio ($/GPa) and E for Composites and Un-reinforced Materials.