Path-designed 3D Printing for Topological Optimized Carbon Fibre Composite Structures

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Abstract: In current 3D printing technologies, it remains a great challenge to print continuous carbon fibre reinforced composites with complex shapes and high mechanical performances. The main reason lies in the limitation of printing path design, which cannot guarantee to print carbon fibres along load transmission paths of composite parts. Here we address this issue by proposing an ingenious path-designed 3D (PD-3D) printing approach that considers the load transmission path and anisotropic property of the continuous carbon fibre reinforced filament. Complex structures of carbon fibre reinforced composites, with enhanced lightweight, were demonstrated. Such structures of carbon fibres paving along load transmission paths, greatly reduce stress concentration and achieve a quasi-isotropic performance. By comparing printed specimens with drilled holes and semicircles, the PD-3D printed specimens with holes and semicircles are 67.5% and 62.4% higher in tensile and flexural strength, respectively. And the strength to weight ratio of the tensile and flexural specimens also increase by 55.1% and 35.2%, compared with the drilled ones.

Keywords: 3D printing; Path design; Continuous carbon fibre; Topological optimization.

1. Introduction

3D printing process, also known as the additive manufacturing, has been investigated for more than 20 years with applications in aerospace, automotive, architecture and medical treatment [1, 2]. The most used printing technologies for polymer resin including ink jet printing [3], fused deposition modeling [4-6], digital light printing [7], stereolithographic printing [8] and laser-assisted laminated object manufacturing [9]. Because every part can be sliced and printed in one direction, 3D printing technologies can nearly build any kinds of parts.

Nowadays, the skyrocketing developments in 3D printing techniques infused more motive power to the traditional composite manufacturing process. The fibre reinforced polymer composite structures

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printed by using Fused Deposition Modelling (FDM) or Fused Filament Fabrication (FFF, analogous to FDM) draws lots of attention, because of the fibres can be easily involved in the FFF printing process. The experimental results show that the mechanical strength of FFF printed specimens improve obviously compared with pure resin samples, even reinforced with chopped fibres [10]. The Oak Ridge National Laboratory (ORNL) manufactures the short carbon fibre reinforced thermoplastic composite parts by using Big Area Additive Manufacturing (BAAM) process [11]. Lewicki et al from Lawrence Livermore National Laboratory (LLNL) have reported a method to print short carbon fibre reinforced thermoset composites, with carbon fibre fluid to be aligned in three dimensions and cured into complex geometries [12]. Impossible Objects and Markforged companies [13] also provide products for short or continuous fibre reinforced composite printing.

For the FFF printing of fibre reinforced polymer composites, the printing path should be carefully designed and adjusted. Because the printing path determines the strength, geometry shape and surface roughness of the printed parts. As shown in Table 1, four different kinds of printing methods for fabricating fibre reinforced composite parts are distinguished and reviewed, including straight printing, in-plane non-interlace printing, in-plane interlace printing and out-of-plane printing. The first printing method in the table has a straight fibre path go through the whole part and the rest volume is filled with pure resin. This reinforcing approach is easy to implement, but the one-directional fibre path restricts the multidirectional load bearing possibility. Thus, the in-plane and non-interlace printing method have been proposed to change the fibre deposition direction in two dimensions. The classic printing paths of spiral, contour and zigzag earned lots of applications. All of them have a parallel adjacent path (or parallel tangent of each adjacent path) and each path would not interlace with another one. Compared with the straight printing path, the second method not only improved the tensile strength but also increased the flexural strength and modulus. The third one has the same path generation strategies, but releases the constraints of filaments interlacing. Consequently, honeycomb, Kagome and grid structures are generated to mainly fill the inside volume of the composite part, which can achieve better compressive strength. Because the fibre reinforced filament provides excellent self-supporting property, the three-dimensional structures can be established easily. The out-of-plane or free hanging printing draws lots of attention. However, the unique anisotropic mechanical property of fibre reinforced filament has been ignored. As the key point of the 3D printing of fibre reinforced composites, the load-dependent printing method should be studied and developed. Some research works of the stresses calculation and preliminary comparison have been done in recent years [30,31].

In this paper, an ingenious Path-designed 3D (PD-3D) printing method is presented to manufacturing the complex composite structures by considering the load transmission path and anisotropic property of the filament. The topological optimization method is applied to redesign the complex composite structures mainly into two portions, the scaffold beams and branches. Then, all of the intricate stresses inside the parts are divided into well-organized tensile and compression stresses which can be reinforced by the anisotropic carbon fibres. The tensile testing specimens with a hole and three-point bending testing specimens with a semicircle were printed based on this method. An impregnation system and a chamfered printing nozzle were applied to handle the continuous carbon fibres. The tensile and three-point bending properties of the testing specimens were fabricated to evaluate the new PD-3D printing method. After that, a continuous carbon fibre reinforced bionic-shape suspension structure was manufactured and investigated.

2. 3D printing path design of continuous fibre reinforced composites

The anisotropic property of continuous fibre reinforced composite filaments decide that its maximum strength is along the longitudinal direction of fibre bundles. Therefore, if the load transmission path in the printed part can follow the longitudinal direction of fibre bundles, the composite part can yield a maximum in strength with a minimum of material. At this situation, the printing path is not comprised by solid section or pieces, but instead, the fibre bundles are placed where needed, and this result in very bionic-shape structures.

The Solid Isotropic Material with Penalization (SIMP) method of topological optimization was applied to analyze the load transmission path of the composite structure and removed these sections with low stresses or nearly out of the way of the load transmission. After that, the whole composite structure mainly composed of the scaffold beams and branches. The stresses inside the parts were divided into tensile and compression stresses. The scaffold beams can be fabricated with the anisotropic continuous fibre reinforced filament along one direction. The branches have two or more scaffold beams crossing through and usually show quasi-isotropic properties.

Currently, the continuous fibre reinforced filaments cannot pave along the load transmission path, because the messy stresses distribution of the parts and uncertain restrictions of path planning for the continuous fibre reinforced filaments. Here, we presented a 3D printing path planning method of the continuous fibre reinforced polymer composite for PD-3D printing. The flow chart of this method is shown in Fig. 1. At first, the original design of the part is obtained, the loads and constraints are applied based on the service conditions. Then, the topological optimization is employed to analyze the load transmission path in isotropic material (the algorithm is shown in Fig. S.1 of supplementary material). The direction and intensity of the principal stresses (tensile and compression stresses), filament dimension, interference and a minimum twist angle of the fibre should be taken as boundary conditions for the printing path design. Finally, the G-code file is generated and used to control the printing system.

3. Experimental

3.1 Materials and printing devices applied

The 1K 66tex HT T300 carbon fibre is from Toray Industries (density: 1.76 g/cm^3, diameter of single fibre: 7 μm, weight: 66 g/10^{3}m), the 910 nylon filament is from Taulamn3D (diameter: 2.85 mm, density: 1.08 g/cm^3, printing temperature: 250 ^{o}C-255 ^{o}C). The PA845H-PL nylon sizing agent (Michelman company) was applied for the surface modification of the continuous carbon fibres. The 3D printer used in this work has a developed printing head to impregnate the carbon fibre with thermoplastic resin in the heating block (the printing equipment is shown in Fig. S.2 of supplementary material). The printing bed has a dimension of 210 mm width and 400 mm long and can move in X and Y directions. The highest printing height is about 380 mm. The schematic diagram of new 3D printing head for continuous fibre reinforced filaments printing is shown in Fig. 2 (a). The 3D printing of continuous carbon fibre reinforced filament turns the extrusion process into a pultrusion process. Because the composite filament adheres to the printing bed and provides a traction force to pull the filament out of the nozzle. The carbon fibre do not need to feed, and have the same moving speed with the printing process. A narrowed output is designed to compress the filament and decrease its voids contents.

A sponge foam infilled with PA845H-PL nylon sizing agent is applied to infiltrate the carbon fibre bundles and improve the bonding strength between fibre and resin matrix, as shown in Fig. 2 (b). The cooling block is used to decrease the thermal heat of the thermoplastic resin, which transfers from the heating block, and ensure a continuous feeding process. The constant feeding speed of the thermoplastic resin depends on the printing speed and the diameter of thermoplastic filament. The distance between the nozzle and the printing bed is about 0.2 mm (layer height). A special chamfered shape of the printing nozzle is designed and machined to prevent the breakage of the carbon fibre bundle and to give a high compaction pressure to the filament. In addition, a cooling fan was applied to cool the filament when it was printed on the printing bed. The open source control software Repetier-Host was used to communicate with the Megatronics v3.2 control board. The heating temperature is set to 250 ^{o}C and the printing speed is about 4 mm/s.

3.2 Specimen preparation

Four kinds of carbon fibre reinforced nylon composite tensile test specimens (TO, TX, TD and TE) and three flexural test specimens (BX, BD and BE) were printed and compared. The tensile specimens have a standard dog bone shape with 165 mm length, 75 mm gauge length, 13 mm width and 1 mm thickness, and a 3.5 mm diameter hole in the centre. The flexural specimens are 95 mm long and 12.5 mm width, 3 mm thickness and a 20 mm diameter semicircular in the centre (15 mm chord length, the smallest width is 7 mm). TO, TX and TE specimens were printed by using PD-3D printing method. The TO specimen has an enhanced fibre path (based on the topological analyzing results) between two layers and a circular hole in the centre. TX and TE specimens both have an elliptical hole in the centre, but only the TX has the enhanced fibre path. TD specimen was printed by a solid rectangular infill of continuous carbon fibre reinforced filament and drilled with a 3.5 mm diameter circular hole after the printing process. Similarly, BX and BE specimens were PD-3D printed, and BX specimen had an enhanced fibre path following the topological calculation results. The BE specimen did not have the enhanced fibre path and the BD specimen was printed by solid rectangular infill and machined with a semicircular hole after the printing process. A three-point bending fixture with a 72 mm length of span and column supports was used for testing. Except for the testing specimens, a scaled-down suspension plate was applied to fabricate the bionic composite structures with load-bearing abilities. The dimensions of the specimens and suspension plate are shown in Fig. S.3 of the supplementary material. The carbon fibre volume percentage of these specimens was around 28%. A universal electronic testing machine INSTRON 4045 with CCD digital image strain camera and SCHENCK 63KN machine were applied to test the specimens. The testing speed of tensile and flexural specimens were 2 mm/min and 2.5 mm/min, respectively. A OLYMPUS BX60M microscope was employed to investigate the internal quality of the printed specimens. The HyperWorks OptiStruct solver was used for the topological analysis, and the properties of isotropic 910 nylon resin material were employed, including 53.4 MPa tensile strength, 502 MPa tensile modulus and 0.39 Poisson's ratio.

4. Results and Discussion

4.1 Printing path of the continuous carbon fibre reinforced composite specimens

The printing path of continuous carbon fibre reinforced nylon composite specimens were designed based on the path planning method for PD-3D printing, as shown in Fig. 3. According to the topological analysis results of the composite parts, carbon fibres should reinforce the high-stresses area (red colour) to enhance the strength. Generally, the fibre path that follows the contour of the calculated shape is used, such as the solid areas of the tensile and the flexural specimens shown in Fig.3 (b). The optimized flexural specimen has reinforced beams like a bridge. Thus, the enhanced printing path is to overcome the weakness of the anisotropy of carbon fibre reinforced filament, such as the 45^{o} path around the hole of the tensile specimen, the reinforcing bridge-like fibre path of the flexural specimen and the scaffold path of the suspension plate. And the scaffold path is applied to the branch areas which have stresses in different directions, for example, the clamping area of the tensile specimens shown in Fig.3 (a) and the branch areas of the suspension plate.

The topologically optimized shape of the suspension plate has major, minor and medium stresses, as illustrated in Fig. 3 (c). The major and minor stresses represent the tensile and compression stresses, and the medium stresses are the combined stresses of the major and minor ones. The stress distribution of the suspension plate indicates that the anisotropic beams are used to bear stretch and compression load. The branch areas have lots of medium stresses and should utilize the scaffold path to achieve a quasi-isotropic property as we described in section 2. For the sake of continuous printing, the outskirt path is created to connect the different path in one layer (with an acceptable twist angle of the fibre), as illustrated in Fig. 3 (d). The jump point is set to change the printing process from one layer to another, usually following with a lift of Z axis. The 1.2 mm thickness suspension plate (6 layers) is printed and shown in Fig. 3 (e).

4.2 Comparison of strength and strength to weight ratio of the printed specimens

The setup for mechanical testing and the measured strength of the tensile and three-point bending specimens are shown in Fig. 4 (the printed specimens are shown in Fig. S.4 of supplementary material). A high-speed CCD (Charge Coupled Device) camera is employed to take photos of the specimens and the strain were calculated by using Matlab code, and the three-point bending test fixture is shown in Fig. 4 (a). The tensile strength and modulus of four specimens are exhibited in Fig. 4 (b) and (d). Obviously, the TX specimen has the highest tensile strength of 460 MPa, and the highest tensile modulus value of 617 MPa belongs to the TE specimen. Comparing with the TD specimens with a drilled hole, the tensile strength of TO, TX and TE specimens increase 29.4%, 67.5% and 58.6% respectively, and the tensile modulus of these specimens improve 24.8%, 22.3% and 22.6%. With regard to the flexural test specimens, the BX specimen has the highest strength of 461 MPa, as illustrated in Fig. 4 (c).

With an elliptical hole, rather than a circular hole in the centre of the TX and TE tensile test specimens, a better tensile strength and stiffness can be achieved, as shown in Fig. 5 (a). The strength to weight ratio (S/W) of the TX and TE specimens are 55.1% and 75.8% higher than the TD specimen respectively, as shown in the statistical results of strength to weight ratio of the tensile specimens in Fig.5 (b). Because the TE specimens with the elliptical holes are lighter than the TX specimens. The curves of flexural strength of three specimens of different types are shown in Fig. 5 (c). All of the specimens have three stages, first is elasticity and second is viscidity, then is the failure of carbon fibres. Comparing the elastic modulus of the three specimens, we can see that the bridge-like fibre path reinforced BX specimen has the highest modulus. The viscidity stages of these specimens indicate the fibre slippage in the nylon matrix and finally, the fibres that are in the centre of the semicircular hole are broken. The strength to weight ratio of the BE and BX flexural specimen is 46.2% and 35.2% higher than the BD specimen, respectively, as illustrated in Fig. 5 (d). But for the BX specimens with a bridge-like reinforced path, the increased strength to weight ratio is lower than for the BE specimens, similar to the S/W difference of TX and TE specimens in Fig. 5 (b). The reason may be because the reinforcing carbon fibres between two layers introduced more resin and weak bonding areas, as discussed in the microscope pictures of Fig. 7. Its contribution to strength is less than the increase of the weight resulting in lower S/W values.

Lots of strong and lightweight composite structures can be found in nature. Tree hole shows optimized shapes for minimizing shear stresses between the wood fibres, and generate an elliptical shape around the hole, as shown in Fig. 6 (a). According to the mechanism analyzing results, the central stress δ_e of the elliptical hole is much lower than the central stress δ_c of a circular hole [32]. That is the reason why TX and TE specimens have higher strength than the TO specimen. The curved carbon fibres around the circular hole (TO specimens) may also decrease the transmission efficiency of tensile load. Obviously, if the fibres around the hole are cut by the tool (as the green fibres of the TD specimen), the discontinues load transfer occurred and results in the lowest tensile strength.

By analyzing the microscopic images of the cross-section of the flexural and tensile specimens as illustrated in Fig. 7, the internal quality and degree of compaction are investigated. Fig. 7 (a) is the cross-section of the flexural specimen and Fig. 7 (b) is the contact area of two filaments in one layer (marked as yellow arrows in Fig. 7 (b) and (d)). Furthermore, through overlapping two adjacent filaments, large rhombic holes are eliminated in our PD-3D printed parts. Obviously, each carbon fibre is covered by the nylon resin and fewer defects can be found in these printed specimens. We can notice that by giving a high compaction pressure to the filament, the degree of compaction is comparable to the pressure assisted hot-press heating method. By studying pixels ratio of the voids to the whole area, the average value of the void contents of printed specimens were calculated and is about 2.1%. The voids and defects may due to the impurity and evaporation of water in the resin material. Because the polyamide material has a strong hygroscopic property. The 45° reinforced fibres are introduced and bring more nylon resin into the tensile specimens, as shown in Fig. 7 (c), the distance between two layers are higher than the one without reinforced fibres. In Fig.7 (c), the 45° fibres show a larger area of the resin matrix than the 0° fibres. Moreover, the deformation of 45° fibres leads to a larger resin rich-area than the unreinforced one, as illustrated in Fig. 7(d).

4.3 Comparison of the PD-3D and traditional method printed suspension plates

The tensile strength and strength to weight ratio of the PD-3D printed suspension plate are compared with the suspension plate of the original shape printed by the traditional printing method with nylon filament, as shown in Fig. 8. This bionic structure can only be printed by using the PD-3D printed method. Whereas the traditional printing method cannot handle filaments with continuous carbon fibres infill, even the state of the art carbon fibre printers. Thus, the object of comparison for this experiment is the pure nylon resin printed suspension plate, which is fabricated by 100% infill of the contour printing path. The PD-3D printed suspension plate has a thickness of 1.2mm and 7.6g weight and the nylon part is 6.7mm thickness and 38g weight, as demonstrated in Fig. 8 (a). Owing to the small thickness of the PD-3D printed part, it starts to deform after 0.3mm displacement. The strength of the initial testing stage of the PD-3D printed suspension plate was calculated and compared with the N-3D nylon plate. The testing result indicates that the strength to weight ratio of the PD-3D printed part is 16 times higher than the nylon suspension plate fabricated by the traditional printing method.

5. Conclusions

In this work, the state of the art of 3D printing carbon fibre reinforced polymer composite parts has been explored. A new path-designed 3D printing method for the fabrication of complex structures with continuous carbon fibre reinforced nylon composite is presented. The load transmission path of the parts and the anisotropic properties of continuous carbon fibre reinforced filament were mainly considered to design the printing path of the printing process. Compared to the printed specimens that contained a machined hole and semicircle, the PD-3D printing method provides 67.5% and 62.4% higher tensile and flexural strength respectively. The strength to weight ratio of the tensile and flexural specimens also increase by 55.1% and 35.2% compared to the machined ones. The strength to weight ratio of the PD-3D printed scaled-down suspension plate is 16 times higher than the nylon suspension plate fabricated by the traditional printing method. This work shows the outstanding potential of the 3D printing technologies for production of complex continuous carbon fibre reinforced composites. This robust PD-3D printing technology path planning method can be used to complex composites with stronger and lighter structure requirements, as long as the regular stresses distribution can be obtained. In the future, this method will be developed further more to three-dimensional space and combined with fibre cutting abilities.

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Reference

[1] Goh D, Agarwala S, Goh L, Dikshit V, Sing L, Yeong Y. Additive manufacturing in unmanned aerial vehicles (UAVs): Challenges and potential. Aerosp Sci Technol 2017;63:140-151.

[2] Wong KV, Hernandez A. A Review of Additive Manufacturing. ISRN Mech Eng 2012;2012:1-10.

[3] Choi M, Heo J, Choi D, Hwangbo S, Hong J. Inkjet Printing Based Layer-by-Layer Assembly Capable of Composite Patterning of Multilayered Nanofilms. Macromol Mater Eng 2017;302(12):14496–14502.

[4] Ngo TD, Kashani A, Imbalzano G, Nguyen KTQ, Hui D. Additive manufacturing (3D printing):A review of materials, methods, applications and challenges. Compos B Eng 2018;143:172–196.

[5] Parandoush P, Lin D. A Review on Additive Manufacturing of Polymer-Fiber Composites. Compos Struct 2017;182:36-53.

[6] Wang X, Jiang M, Zhou Z, Gou J, Hui D. 3D printing of polymer matrix composites: A review and prospective. Compos B Eng 2017;110:442-458.

[7] Mu Q, Wang L, Dunn C, Kuang X, Duan F, Zhang Z, Qi HJ, Wang T. Digital light processing 3D printing of conductive complex structures. Addit Manuf 2017;18:74-83.

[8] Yan X, Gu P. A review of rapid prototyping technologies and systems. Comput Aided Des 1996;28(4):307-318.

[9] Parandoush P, Tucker L, Zhou C, Lin D. Laser assisted additive manufacturing of continuous fiber reinforced thermoplastic composites. Mater Des 2017;131:186-195.

[10] Dickson AN, Barry JN, McDonnell K, Dowling DP. Fabrication of continuous carbon, glass and Kevlar fibre reinforced polymer composites using additive manufacturing. Addit Manuf 2017;16:146-152.

[11] Kishore V, Ajinjeru C, Nycz A, Post B, Lindahl J, Kunc V, Duty C. Infrared preheating to improve interlayer strength of big area additive manufacturing (BAAM) components. Addit Manuf 2017;14:7-12.

[12] Lewicki JP, Rodriguez JN, Zhu C, Worsley MA, Wu AS, Kanarska Y, Horn JD, Duoss EB, Ortega JM, Elmer W, Hensleigh R, Fellini RA, King MJ. 3D-Printing of Meso-structurally Ordered Carbon Fiber/Polymer Composites with Unprecedented Orthotropic Physical Properties. Sci Rep 2017;7:1-13.

[13] Chapiro M. Current achievements and future outlook for composites in 3D printing. Reinf Plast 2016;60(6):372-375.

[14] Yao X, Luan C, Zhang D, Lan L, Fu J. Evaluation of carbon fiber-embedded 3D printed structures for strengthening and structural-health monitoring. Mater Des 2017;114:424-432.

[15] Nakagawa Y, Mori KI, Maeno T. 3D printing of carbon fibre-reinforced plastic parts. Int J Adv Manuf Technol 2017;91:5-8.

[16] Baumman F, Scholz J, Fleischer J. Investigation of a New Approach for Additively Manufactured Continuous Fiber-reinforced Polymers. Procedia CIRP. 2017;66:323-328.

[17] Li N, Li Y, Liu S. Rapid prototyping of continuous carbon fiber reinforced polylactic acid composites by 3D printing. J Mater Process Technol 2016;238:218-225.

[18] Ferreira RTL, Amatte IC, Dutra TA, Bürger D. Experimental characterization and micrography of 3D printed PLA and PLA reinforced with short carbon fibers. Compos B Eng: Engineering 2017;124:88-100.

[19] Justo J, Távara L, García-Guzmán L, París F. Characterization of 3D printed long fibre reinforced composites. Compos Struct 2017;185:1-32.

[20] Dickson AN, Barry JN, McDonnell KA, Dowling DP. Fabrication of continuous carbon, glass and Kevlar fibre reinforced polymer composites using additive manufacturing. Addit Manuf 2017;16:146-152.

[21] Tian X, Liu T, Yang C, Wang Q, Li D. Interface and performance of 3D printed continuous carbon fiber reinforced PLA composites. Compos Part A Appl Sci Manuf 2016;88:198-205.

[22] Matsuzaki R, Ueda M, Namiki M, Jeong TK, Asahara H, Horiguchi K, Nakamura T, Todoroki A, Hirano Y. Three-dimensional printing of continuous-fiber composites by in-nozzle impregnation. Sci Rep 2016;6:1-7.

[23] Lu C, Qi M, Islam S, Chen P, Gao S, Xu Y, Yang X. Mechanical performance of 3D-printing plastic honeycomb sandwich structure. Int J Pr Eng Man Gt 2018;5(1):47-54.

[24] Agarwal K, Kuchipudi SK, Girard B, Houser M. Mechanical properties of fiber reinforced polymer composites: A comparative study of conventional and additive manufacturing methods. J Compos Mater 2018;52(23):3173-3181.

[25] Hao W, Liu Y, Zhou H, Chen H, Fang D. Preparation and characterization of 3D printed continuous carbon fiber reinforced thermosetting composites. Polym Test 2018;65: 29-34.

[26] Compton BG, Lewis, JA. 3D-printing of lightweight cellular composites. Adv Mater 2014;26(34): 5930-5935.

[27] Liu S, Li Y, Li N. A novel free-hanging 3D printing method for continuous carbon fiber reinforced thermoplastic lattice truss core structures. Mater Des 2018;137:235-244.

[28] Eichenhofer M, Wong JCH, Ermanni P. Continuous lattice fabrication of ultra-lightweight composite structures. Addit Manuf 2017;18:48-57.

[29] Prüß, H, Vietor T. Design for Fiber-Reinforced Additive Manufacturing. J Mech Des 2015;137(11):1-7.

[30] Dickson, A. N., Dowling, D. P. Enhancing the bearing strength of woven carbon fibre thermoplastic composites through Additive Manufacturing. Compos Struct 2019;212:381-388.

[31] Zhang, H., Yang, D., Sheng, Y. Performance-driven 3D printing of continuous curved carbon fibre reinforced polymer composites: A preliminary numerical study. Compos B Eng: Engineering 2018;151:256-264.

[32] Mattheck C, Tesari I. The mechanical self-optimisation of trees. WIT Trans Ecol Environ 2004;73:197-206.

Figure and Table Captions

Fig. 1 Flow chart of the new path-designed 3D printing method of fibre reinforced polymer composites.

Fig. 2 Schematic diagram of new 3D printing head for continuous fibre reinforced filaments printing, (a) impregnation diagram of carbon fibre and resin matrix, (b) illustration of the printing head.

Fig. 3 Topological calculation and printing path design of the testing specimens and the suspension plate, (a) analyzed element density based on load distribution and printing path of the tensile testing specimen, (b) element density and printing path of the three-point bending specimen, (c) topological analyzing process of the scaled-down suspension plate, (d) printing path of the suspension plate, (e) PD-3D printed suspension plate.

Fig. 4 The setup for mechanical testing and the measured strength of the tensile and three-point bending specimens, (a) tensile and three-point bending test fixture and CCD strain monitoring, (b) tensile strength of four specimens with standard error, (c) flexural strength of three specimens with standard error, (d) tensile modulus of four specimens with standard error.

Fig. 5 Tensile and flexural testing results and strength to weight ratio of different specimens, (a) tensile strength curves of four specimens, (b) statistical results of strength to weight ratio of the tensile specimens, (c) curves of flexural strength of three specimens, (d) statistical results of strength to weight ratio of the flexural specimens.

Fig. 6 Investigation of the mechanical difference of tensile test specimens. (a) a tree hole that shows the growing direction of the wood fibres [32] and the stresses distribution around the hole, (b) fibre path of four tensile specimens and the printed specimens.

Fig. 7 Optical microscopic of the cross-section of the flexural and tensile test specimens, (a) cross-section of the flexural test specimen, (b) contact area of the printed filaments of flexural specimen in one layer, (c) cross-section of the tensile test specimen with 45° reinforcing fibres, (d) contact area of the printed filaments of tensile specimen in one layer.

Fig. 8 Comparison of tensile strength and strength to weight ratio of PD-3D printed suspension plate and traditional printing method fabricated nylon suspension plate of the original shape. (a) pictures of the test suspension plates printed by PD-3D and traditional method, (b) tensile testing curves of the two plates.

Table 1. Four different FFF printing methods for fibre reinforced composite parts.