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AN INVESTIGATION ON STRUCTURE STIFFNESS OF 3D PRINTED FRAMES USING CONTINUOUS CARBON FIBERS

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ABSTRACT

In this paper, the effect of continuous carbon fibers (CCF) on the stiffness of 3D printed frames is investigated. Fused deposition modelling (FDM) technology is employed to build three typical frames with 15% of CCF and 85% poliamide 12 which is combined 10% short carbon fibers (PA12-CF) for compress testing. The 3D models of the frames including grid (-45^0/+45^0), triangle (-60^0/+60^0) and grid (0/90^0) made by CCF lattices are designed based on slicing parameters and simulated in Abaqus before conducting experiment. An MTS–45 system (USA) is used for compression testing to obtain the stiffnesses and peak loads of the models. The effect of different CCF lattices on the stiffness of the printed models is pointed out. Finally, the comparison between simulation and experiment results are also discussed. It shows that two results are quite close together. This investigation is worth in the extension of CCF printing application.

KHẢO SÁT VỀ ĐỘ CỨNG KẾT CẤU CỦA KHUNG IN 3D SỬ DỤNG SỢI CARBON LIÊN TỤC

Hoàng Tiến Đạt
Trường Đại học Công nghiệp Hà Nội

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TỪ KHÓA

Sản xuất bồi đắp
Vật liệu in 3D composite
Cấu trúc lưới in 3D
Sợi gia cường carbon liên tục
Độ cứng cấu trúc in 3D

TÓM TẮT

Trong bài báo này, ảnh hưởng của sợi carbon liên tục (CCF) tới độ cứng của khung in 3D được khảo sát. Công nghệ đùn mẫu chảy (FDM) được sử dụng để chế tạo 3 mô hình khung đặc trưng sử dụng 15% CCF và 85% vật liệu polymer PA12 đã được pha trộn thêm 10% sợi carbon cắt ngắn (PA12-CCF) phục vụ quá trình khảo sát nén. Mô hình in 3D của 3 khung CCF bao gồm cấu trúc lưới nghiêng (-45^0/+45^0) cấu trúc tam giác (-60^0/+60^0), cấu trúc lưới (0^0/90^0) cũng được thiết kế dựa theo các thông số hình học sau khi cắt lớp và sử dụng cho quá trình mô phỏng bằng phần mềm Abaqus trước khi thí nghiệm. Hệ thống máy kéo nén MTS-45 của Mỹ được sử dụng cho quá trình nén để đo được độ cứng và lực tới hạn của 3 mẫu. Cuối cùng, các kết quả mô phỏng và thí nghiệm được phân tích, so sánh với nhau và cho thấy khá trùng khớp. Khảo sát này rất hữu ích trong quá trình mở rộng ứng dụng của công nghệ in 3D sử dụng sợi carbon liên tục.

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1. Introduction

Recently, 3D printing has seen its most significant development due to the development of 3D printed materials. The current development of 3D printing technology can be attributed to the advancement of materials used in the printing process and the improvements in the printing principle, along with accompanying software developments [1]. Common applications of 3D printing can be found in various fields such as aerospace, military, rapid prototyping, medical, and education [2]. The biggest advantage of 3D printing is its ability to produce highly complex parts in a single manufacturing process, especially creating structures that traditional machining methods cannot achieve. However, the main drawback of 3D printing methods is that the mechanical properties have not yet reached a level comparable to materials with the same composition and proportions manufactured using traditional methods such as cutting, casting, or molding [3]. Many studies have been conducted to improve the mechanical properties of plastic printed parts [4].

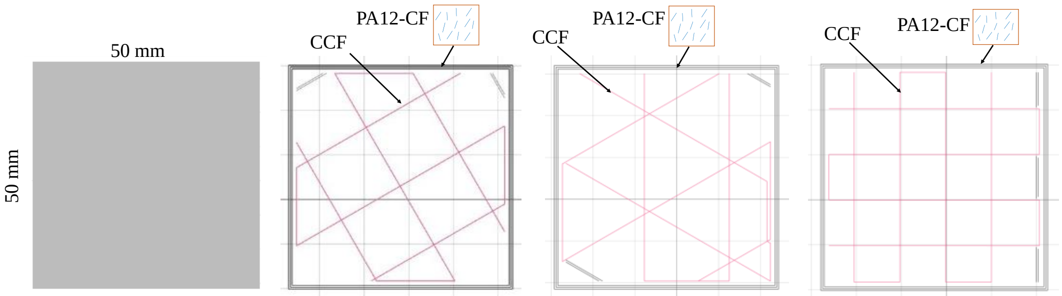
Among some methods to improve mechanical properties of plastic printed parts, combining continuous fiber reinforcement with plastic during the printing process can significantly improve the mechanical properties of parts printed [5]. Yueke Ming et al. focused on optimizing the parameters of the manufacturing process, such as printing speed, printing space, printing thickness, curing pressure, and curing temperature to improve the strength and modulus of the printed continuous carbon fiber (CCF) composite [6]. Besides, Dakota Hetrick et al. investigated the effect of fiber content on mechanical properties of additively manufactured CCF composites [7]. The effect of printing process parameters on the tensile strength of CCF fiber and Polylactic acid [8]. 3D printing technology using reinforcing materials such as carbon fibers, glass fibers is called composite 3D printing technology. In this technology, mixing plastic materials with short-cut fibers can be done using conventional FDM technology. However, the continuous fiber printing process becomes much more complex. The reinforcing fibers need to be separately controlled and mixed with the base material in various ways through dual extruders or composite print heads. However, controlling and arranging these continuous fibers poses many challenges both in printing technology and in optimizing stiffness or strength-to-weight ratios to save on this expensive reinforcing material.

In this paper, the effect of CCF on the structure stiffness of printed frames is studied. Three CCF printed frames including grid ($-45^0/+45^0$), triangle ($-60^0/+60^0$) and grid ($0/90^0$) lattices are designed and fabricated for simulation in Abaqus and experiment steps. From now, the short names of three frames are called as grid 45 CCF, triangle CCF and grid 90 CCF. The stiffness and peak load of each model are measured and analyzed to point out the effect of CCF and designed lattices. The results show the potential application of CCF in FDM 3D printing.

2. Research Procedure

2.1. Simulation models

In this section, three printed models, designed by Autodesk Inventor 2023 software, has a volume of 50 × 50 × 50 mm. The printing slicer Aura from Anisoprint company is used to choose the printing settings and generate the lattice patterns in each case study. This application can replicate and show the printed model exactly like the actual printed model. Three different models will be printed using PA12-CF, and CCF materials (see Figure 1). PA12-CF is used to print wall whereas CCF is used to print the lattice frames. Every printed model is printed at the same time in order to guarantee a solid connection between the printed models and the glass plate. The Aura software created three different lattice frames including Grid 45, Triangle, Grid 90 with CCF. All the models have the same infill density.



(a). 3D model (50 mm height) (b). Grid 45 CCF model (c). Triangle CCF model (d). Grid 90 CCF model

Figure 1. *Simulation of printing structure for three case studies*

2.2. Experiment models

In this study, continuous fiber printing technology is applied. Three models are printed with polyamide 12 combined 10% short carbon fibers (PA12-CF) and continuous carbon fibers (CCF). The material properties of PA12-CF and CCF are given in Table 1. Table 2 shows the normal printing properties parameters. The CCF fiber filament with diameter 0.35mm including more than 1200 mono fibers is illustrated in Figure 2. The printer has two extruders inwhich the first extruder is used to print PA12-CF only and the second one is used to print CCF and PA12-CF simultaneously. The hot PA12-CF resin will mix to hot soft CCF at the printing nozzle with size of 0.6 mm to create likely unidirectional composite laminates. The CCF trajectory is controlled by Aura slicing software. The printer automatically run from the first layer to the final layer to build the structures. Figure 3 shows the printing process of three frame models.

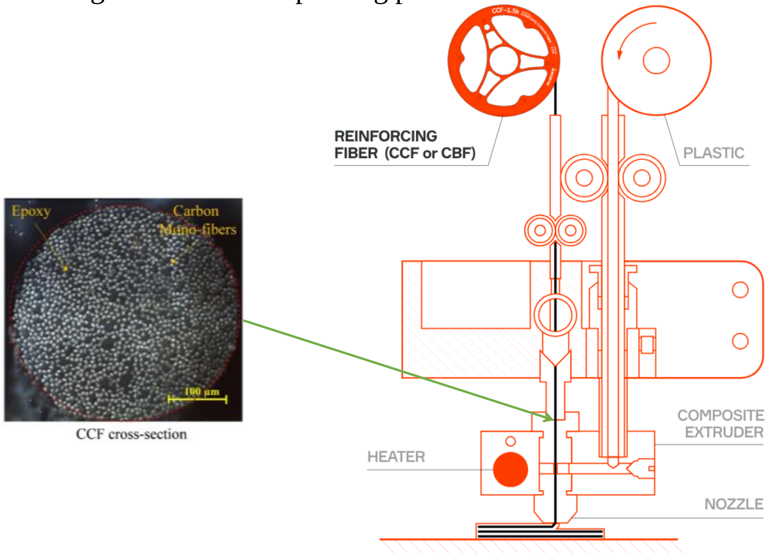


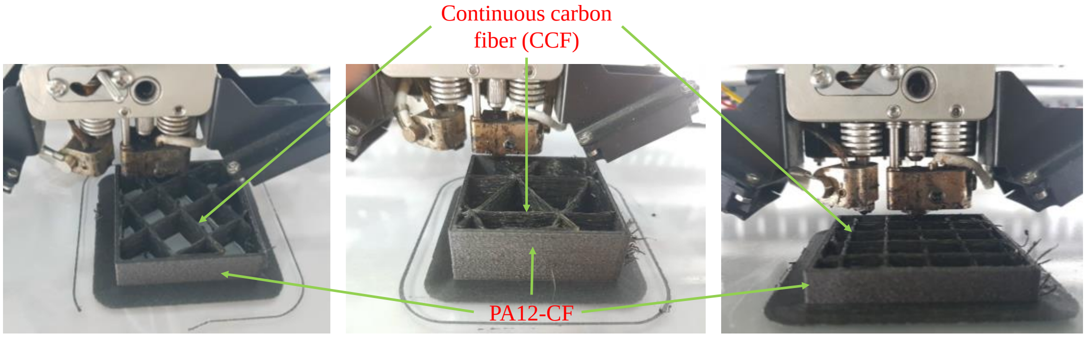
Figure 2. *Extruder technology for printed continuous fiber reinforced platics* [9]

Table 1. *Properties of materials* [9]

Material	Young's modulus (GPa)	Poisson ratio	Density (g/cm^3)	Elongation at break (%)	Tensile strength (MPa)
PA12-CF	5.8	0.3	1.06	25	72
Continuous carbon fiber (CCF) - Anisoprint	150	0.26	1.45	-	2200

Table 2. *Parameters in printing*

CCF layer thickness (mm)	**PA12-CF layer thickness (mm)**	**CCF printing speed (mm/s)**	**PA12-CF printing speed (mm/s)**	**CCF temperature (^{0}C)**	**PA12-CF temperature (^{0}C)**
0.36	0.18	20	60	250	250
Buiding plate temperature (^{0}C)	**CCF line width (mm)**	**PA12-CF line width (mm)**	**Flowrate (%)**	**Grid Infill (%)**	**Wall line of model (-)**
60	0.8	0.4	100	15	3



(a). Printing Grid 45 CCF model (b). Printing Triangle CCF model (c). Printing Grid 90 CCF model

Figure 3. *Printed continuous carrbon fiber and PA12-CF structures*

3. Results and Discussion

3.1. Simulation Result

In this section, the stiffness of three models are predicted by Abaqus software. The model is created by Autodesk Inventor based on the geometrical parameters from slicing software. The element C3D8R is selected for meshing process of three models. Figure 4 show the Von Mises stress and deformed shapes of the model under compress load with 5 mm displacement. Two rigid solid part simulate two clamp of the compressing machine.

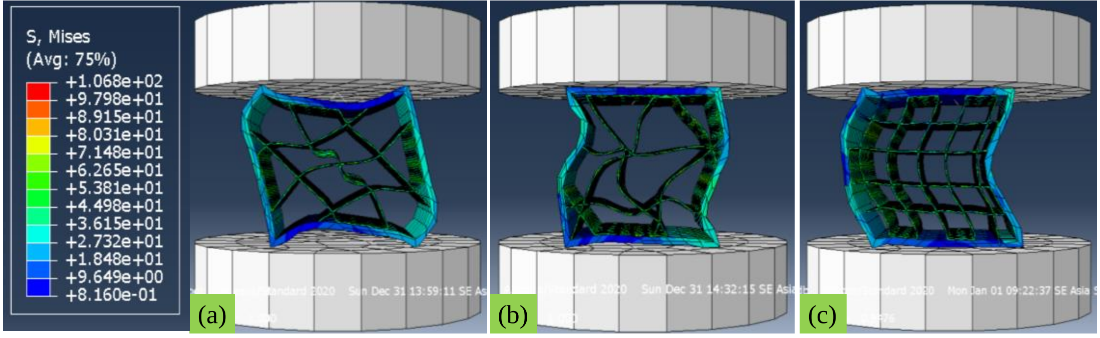


Figure 4. *Von Mises stress and deformed shapes of: (a) Grid 45 CCF model; (b) Triangle CCF model; (c) Grid 90 CCF model*

3.2. Experiment Results

The models, after created from previous process, is printed using the materials in Table 1. The CCF is set on the same trajectory in a Gcode files exported from the slicing software. Figure 5 shows the testing system. The compressing speed is 3 mm/minute. All the results are recorded in the computer for analysing step. The final deformed shapes of three models at 5 mm displacement of the moving clamp are captured in Figure 6. Comparing to the deformed models of the simulation, the experiment deformed printed models have quite similar behaviors. It is pointed out the simulation results are realiable and can be applied for further study. The simulation and experiment results will be discussed more in the next section.

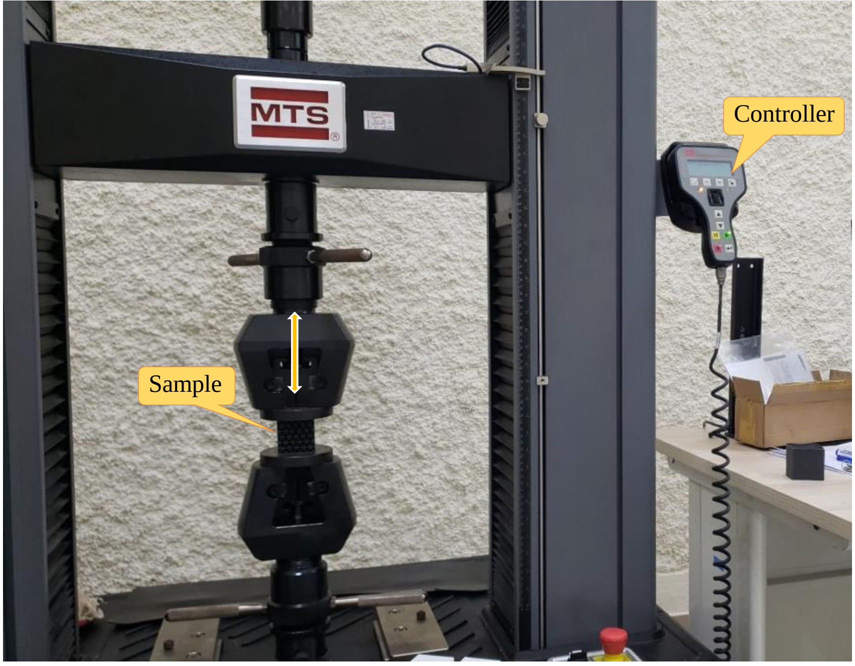


Figure 5. *MTS – 45 system (USA) for compress testing*

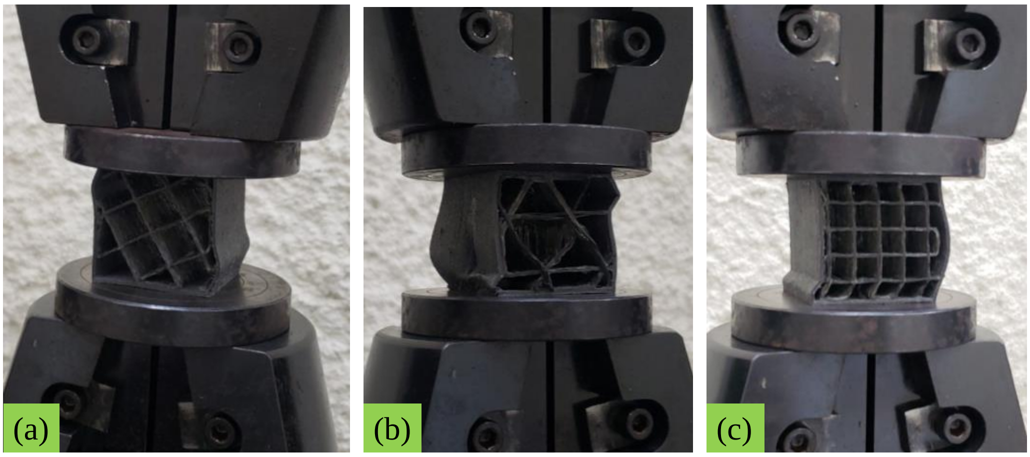


Figure 6. *Compressed models of: (a) Grid 45 CCF model; (b) Triangle CCF model; (c) Grid 90 CCF model*

3.3. Discussion

The load-displacement plot of simulation and experiment results are showed in Figure 7. Those results are quite closed together. However, the experiment peak load or stiffness of each model is smaller than that of simulation one because the simulation models have ignored all defects or errors in the printed models. All the results are given in Table 3. The mass of each model is approximate 33 gam. It can be concluded that the grid 90 CCF model has larger structure stiffness than those of others. Additionally, the force and displacement cure of grid 90 CCF model is more smooth since the load is easily carried in the lattice and the deformation is quite uniform before reaching the peakload.

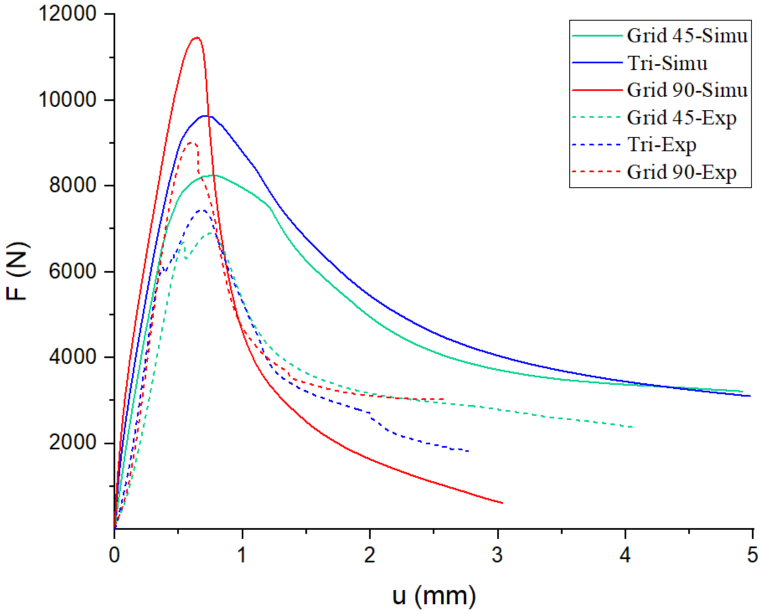


Figure 7. *Comparison between simulation and experiment force and displacement results*

Table 3. *Compress Simulation and Experiment results*

Models	**Simulation**	**Experiment**	**Error (%)**	**Simulation**	**Experiment**	**Error (%)**
	Structure stiffness (N/mm)			**Peak load (N)**		
Grid 45 CCF	16720	14098	15.68	8276	6835	17.4
Triangle CCF	18516	17683	4.5	9645	7458	22.6
Grid 90 CCF	19330	18810	2.69	11460	9020	21.3

4. Conclusion

The CCF plastic printing process using FDM technology is investigated. Three CCF frames with different lattice structures are designed for simulation and experiment study. The comparison of stiffness and peak load of each model are discussed. It shows the acceptable errors between simulation and experiment results. Additionally, although all the models have almost the same masses, the results show that the grid 90 CCF frame has the highest stiffness and peak load where the grid 45 CCF frame has smallest ones due to compressing loading condition. This investigation has useful contribution in the development of CCF 3D printing.

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