Ultrasonic fatigue analysis of 3D-printed carbon fiber reinforced plastic

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Abstract

The development of 3D printing technologies using composite materials has revolutionized additive manufacturing. Using these technologies, various products can be fabricated with strengths beyond the limits of the strength of the polymer used. However, although parts manufactured using carbon fiber reinforced plastic (CFRP) 3D printing have excellent characteristics, research on their durability is lacking, making their application difficult in the real industry. In this study, an ultrasonic fatigue test was conducted on a CFRP material manufactured by 3D printing to evaluate fatigue performance. Because of the characteristics of CFRP, the strength varies depending on the orientation angle of the carbon fiber, and the durability also varies. Therefore, an experiment on three types of specimens mixed in the bi-direction and uni-direction of 0° and 90° was conducted. For the ultrasonic fatigue test, a specimen design with a special shape is required according to the resonance frequency and dynamic modulus of the material. To this end, a specimen was designed based on measurements of the physical properties of the material according to the angle of the fiber, which were verified by Finite element method (FEM) modal analysis, and the fatigue life was estimated through an actual experiment. The fatigue failure life was simulated by FEM fatigue analysis considering the measured fatigue test results and the derived anisotropic properties simultaneously. Additionally, based on the advantages of CFRP 3D printing, which adjusts the fiber pattern, we fabricated a specimen with a concentric pattern to derive the fatigue life and calculate the actual life improvement. Based on the results of this study, the specific rigidity of the CFRP parts can be optimized by adjusting the fiber pattern. Additionally, the results of this study can aid in the analysis of the fatigue characteristics of 3D-printed CFRP materials.

1. Introduction

Fused deposition modeling (FDM) is the most common method for rapid prototyping and self-manufacturing because it can fabricate products with effective mechanical properties at a low cost [1]. However, thermoplastic resins such as PLA, ABS, nylon, and polycarbonate are the primary materials. The material properties typically include a bulk strength of 30–100 MPa and a low modulus of elasticity (in the range of 1.3–3.6 GPa) [1]. Additionally, the material may become weak due to the thicknesses of the laminated filaments and air gap layers, the width and orientation of gap between layers, and interlayer distortion, which are the major variables that affect the mechanical properties [2, 3, 4]. Consequently, the physical properties of the printed parts tend to decrease [5]. Unlike conventional bulk materials, the printed materials have some anisotropy depending on the stacking method; therefore, there is a limit to manufacturing parts with high load resistance.

In contrast, composite materials may be used to prepare polymer matrix composites by mixing reinforcing material of particles, fibers, or nanomaterials with high mechanical performance and excellent functionality into a polymer. Carbon fiber reinforced plastic (CFRP), which is a typical composite, has attracted attention as a plastic-based high-strength and high-elasticity lightweight structure in which long or short fibers are used as reinforcing materials. CFRP or 3D Printed CFRP is fabricated by incorporating an extremely thin carbon fiber (0.005–0.010 mm) [6] into a polymer matrix by impregnation [6], mixing [7], fused deposition [7, 8], and extrusion [9]. When the carbon fiber is magnified at a fine scale, it is observed that carbon atoms in the fibers are bonded parallel to the fiber axis and aligned in one direction, contributing to excellent tensile strength combined with lightweight and low thermal expansion [6]. It is used in various products, such as drones, aircraft, high-performance or eco-friendly vehicles, sea carriers, and bicycles. However, to produce high-quality CFRP, precise adjustments such as the blending and arrangement direction of fibers are required. However, the
production volumes are limited because of the reliance on skilled workers. Moreover, manufacturing parts with complex internal structures is difficult if traditional manufacturing technology is used. To overcome the low mechanical properties of 3D printing parts using polymer materials and the limited mass production of CFRP parts with complex shapes, FDM-type CFRP 3D printers have been developed [10, 11, 12, 13, 14, 15].

The FDM method, a well-known CFRP 3D printing technology, uses heat and pressure from a nozzle to extract and stack fiber-type raw materials in a semi-melted form. The demand for 3D printing continues to increase owing to the advantages of high production speed and excellent specific strength. However, internal defects often occur during processing, or the binding force of the composite matrix is weakened, resulting in the degradation of the mechanical properties. Consequently, its use is limited because it may damage parts and threaten the safety of the user. Therefore, research is being actively conducted to strengthen CFRP 3D printing components and analyze their mechanical properties.

Dickson et al. [11] analyzed the mechanical performance according to the directionality, type (carbon, Kevlar, glass), and volume fraction of the reinforcing fiber in the printed composite in terms of tension and bending. The results proved that the tensile strength per volume of the polymer reinforced with carbon fibers increased the most, up to 6.3 times, than that of the non-reinforced nylon polymer. However, as the volume fraction of the carbon and glass fibers increased, the air inclusion (void) content inside the composite matrix increased, adversely affecting the mechanical performance. Consequently, increasing the fiber content to 33% increased the maximum tensile strength to 444 MPa, which was higher than that of aluminum 6061-T6 (310 MPa).

Oztan et al. [13] analyzed the microstructures of various printed continuous fiber composites with respect to their mechanical properties. Nylon without reinforcement for the control sample; nylon reinforced with PLA, unidirectional Kevlar fiber, nylon reinforced with 45° Kevlar fiber, and nylon reinforced with unidirectional carbon fiber were measured in accordance with ASTM D638 and ASTM D3039 with a 2.41 mm thick dogbone shape specimen. The mechanical properties of the 3D-printed specimen, decreased by 30%–40% compared to those of the conventionally manufactured specimen. Analyzed in conjunction with the SEM microstructure, it was confirmed that the non-reinforced polymers were weakened by cross-hatch, fiber tow gap, surface roughness, micropores, and reinforced polymers owing to poor interfaces between the fiber tow and poor binding between the reinforcement and fiber and base material.

Consequently, the excellent technical value of 3D-printed CFRP composites are expected to overcome the limitations of existing 3D printing and composites, leading to application in the next generation in the fields of aerospace, automation, urban air mobility, and sports goods. However, most 3D-printed CFRP components are used primarily in conceptual prototypes or research stages, rather than functional components. In other words, extensive industrial applications are limited because CFRP manufactured by 3D printing lacks an accurate evaluation of its strength and function as a load-supporting part.

Filaments are manufactured by mixing polymer pellets and short fibers in a blender and then using an extruder. A secondary extrusion process is performed to ensure uniform distribution of fibers and longitudinal alignment [9]. Based on the 3D CAD shape, the manufactured material is laminated with the polymer according to the mixing ratio and process parameters of the orientation angle to manufacture the 3D-printed CFRP part. The fiber orientation and porosity of a CFRP composite play important roles in determining the properties of the final composite component.

At the same time, analysis of fatigue life is essential. It is important even in quasi-static tensile, compression, and shear stress situations, but it operates as a fatal defect when impact or vibration caused by external loads occurs. Additionally, because it exhibits anisotropy according to the stacking orientation angle, it is necessary to identify the lifespan accordingly and reflect it in the product design. When this fatigue life is measured using an existing hydraulic tester, long-term research is required to evaluate the life of each case according to changes in all the process conditions of the material, lamination conditions, mixing rate, and orientation angle. The problem is that they cannot keep up with the materials and processes of rapidly developing products in the industry.

Therefore, in this study, the fatigue characteristics of 3D-printed CFRP specimens were analyzed using ultrasonic fatigue tests that evaluated their life in a short time by resonating the specimen at 20 kHz. Unlike the traditional fatigue test, the ultrasonic fatigue test is conducted at a high stress application rate of 20 kHz. The standard for measuring and judging the fatigue life of a material ranges from about 10^5 cycles to 10^9 cycles, and sometimes 10^6 cycles are measured as needed. In this case, if the ultrasonic fatigue test is applied, it can measure up to 10^6 cycles in about 1 min, enabling economical and efficient test analysis. In addition, since one end of the specimen is not fixed and stress is applied using the resonance of the part, the error due to axial alignment can be sufficiently ignored, so that the R = −1 stress ratio can be accurately measured. To resonate the specimen and calculate the fatigue load accurately, the natural frequency was measured according to the stacking orientation angle. The dynamic elastic modulus was derived using this equation, and the resonance specimen was precisely designed by modeling the gauge length and resistance length of the dogbone-shaped specimen. To verify the specimen design before the ultrasonic fatigue test, a composite specimen of the carbon fiber and onyx was modeled according to the orientation angle using ANSYS composite prep post. A modal analysis was performed to verify that it vibrated in a longitudinal tensile compression mode at 20 kHz. The verified specimen was manufactured using 3D printing. The fatigue life was measured for up to 10^6 cycles. Finally, we analyzed the fracture pattern according to each fatigue load and life cycle. The characteristics of the fracture surface were observed under a microscope to perform a life-linked analysis.

2. Ultrasonic fatigue test in composites

Composites have been prominently used in the aircraft industry. High-performance composites reinforced with long fibers of carbon, glass, boron, or Kevlar have been highlighted for their excellent fatigue life. Under the tension-tension condition at a stress ratio (R) of 0 or more, the fatigue strength of an aluminum alloy is 30% of the tensile strength and 50% or less of the metal. However, CFRP has fatigue strength of at least 40%–90%, and thus has excellent fatigue strength [16]. This implies that fatigue life is not a key parameter when manufacturing aircraft parts with CFRP. However, the fatigue durability of CFRP varies significantly depending on the strength of the fiber and matrix as well as [5] the process parameters such as the lay-up sequence, manufacturing process, or discontinuity. It is damaged more by shear or compression loading than metal [17]. Therefore, a study on the ultrasonic fatigue test for predicting fatigue life in a relatively short time for various parameters of CFRP and GFRP has been reported.

C. Bathias [17] summarized the differences between high-performance polymer matrix composite materials and metallic materials from the perspective of fatigue. First, the specific durability of the composite material under a periodic tensile load was generally higher than that of the metal. Second, the composite material was less sensitive to the notch effect than the metal. Third, the periodic compressive load caused serious damage to the composite material. Fourth, the impact damage is a key factor in predicting fatigue durability, particularly in compression. Fifth, the giga cycle fatigue of the composite is unknown compared to that of metal. Particularly, there is a lack of understanding of the damage caused by heat generation. Sixth, the specificity of composite fatigue consists of damage mechanics such as transverse cracking, delamination, debonding, edge effects, thickness, and the stacking order.

Backe et al. [18, 19] developed a three-point bending fatigue system that could test CFRP specimens at a frequency of 20 kHz and a maximum deflection displacement of 60 μm. The frequency was tested at 20 kHz.
using a piezoelectric effect, and the cycle was counted by controlling the frequency with a 1D laser Doppler vibrometer (LDV). In the constant amplitude test, as the number of delamination cycles increased in the 10^6 cycle area, the allowable shear stress amplitude decreased, and a runout of 10^6 cycles or more was observed below 5.15 MPa. The real-time temperature distribution measured by IR thermography, showed an increase of 5 °C from the ambient temperature in the undamaged specimen. A delamination crack orthogonal to the fiber direction was observed in the fracture because of friction from internal damage; the temperature increased to a maximum of 45 °C. Additionally, in approximately 30% of the specimen life, a 90° crack occurred in the matrix debonding, and fine peeling occurred between 0° and 90° after approximately 35%. At this stage, an average decrease in stiffness of approximately 4% was measured, and after 70% of life, the rigidity was significantly reduced with the occurrence of interlayer exfoliation.

Lee et al. [20] performed a very high cycle fatigue (VHCF) test on a GFRP composite (PA66-GF30) at 20 kHz. A system was developed for the precise dynamic modulus measurement of specimens, and for specimens stacked with glass fiber (GF) at orientation angles of 0°, 45°, and 90°. Conventional hydraulic fatigue of 3 Hz and VHCF of 20 kHz were tested at the same stress ratio (R = −1). The coefficients of the dynamic elasticity were measured at 8.9 GPa, 4.8 GPa, and 3.9 GPa, respectively, at 0°, 45° and 90°; a resonance specimen was designed based on them. The GF had the highest fatigue strength at 0° (tension in the fiber direction), and overall, the slope of the SN curve of the ultrasonic fatigue test result was lower than that of the conventional fatigue test. This is because of the debonding effect and cyclic softening of various factors such as voids and microcracks in the load direction around the end of the fiber. In the microstructure analysis of the fracture surface, the 0° specimen was observed with the GF arranged in the longitudinal direction of the fatigue stress, and the 45° specimen was observed in a combination of vertical and horizontal directions. 90° were arranged in the vertical direction, voids were observed in the 0° specimen, and the stress concentration in the lamellar structure of the polymer confirmed the fiber delamination in the 45° specimen.

3. Finite element analysis of composite

Although composite materials are modern, they are not widely used because of various concerns. Particularly, the analysis of mechanical properties is very complicated because the material is anisotropic and heterogeneous. Therefore, in addition to the aforementioned experimental studies, an analysis was conducted to simulate the stacking orientation angle, layer, and mixing ratio of the base material and reinforcement using finite element modeling to predict deformation and damage due to external forces in the virtual environment.

In previous studies, only the x-, y-, and z-axial properties were input for the Young's modulus, Poisson's ratio, and shear modulus (G) of a single material model to implement directionality [21], or representative properties were input with shell elements for each layer. The former has a disadvantage in that it is not possible to consider a change in strength according to the shape variable of an actual model because the representative properties of the tensile strength and shear strength are reflected as they are on the x-, y-, and z-axes. In the latter case, the directionality according to the laminated layer and the shape variables of the entire part can be considered, but modeling requires considerable time and effort.

The analysis of the composite model was performed using ANSYS Workbench. It can effectively interpret complex assemblies with components of other materials, along with steel flanges, as well as individual composite components. Moreover, it is possible to define the actual fiber vectors for complex shapes and to visualize the layer with the cross-section of the parts [22].

4. Specimen design

4.1. 3D printing CFRP

The specimen that was fabricated to evaluate the ultrasonic fatigue life of 3D-printed CFRP was composed of an Onyx base material with carbon fiber reinforcement laminated and manufactured using the dual-nozzle FDM method. According to Markforged's Material Data Sheet [23], a 3D printer X7 manufacturer was used in this study. The matrix material Onyx reinforces nylon, a thermoplastic resin, with chipped carbon fiber. The fibers were cut into fine pieces before being extruded into spools, mixed into thermoplastic, and laminated in a heater, extruded, and cooled using the FDM 3D printing method. Onyx is fibers are added to improve the properties of low-grade materials, and the fibers disperse and withstand stress applied. It exhibits excellent surface roughness and is used as a material for providing chemical and heat resistance.

Carbon fiber filaments are supplied to other nozzles and laminated as reinforcement. It improves the strength, rigidity, and dimensional stability of parts, making them 1.4 times stronger and harder than basic ABS. The amount of fiber and length of the chipped segment affects the strength and quality of the part, and fibers below a certain threshold improve the surface roughness and print quality. When the threshold is exceeded, a stronger material may be obtained by mixing a large amount of fibers; however, the surface roughness and component accuracy are reduced because of the low ratio of the base material. Carbon fiber, a reinforcing material, is used to achieve metal strength as part of its weight by adding continuous strands in 3D printing.

The printing process is a continuous fiber fabrication (CFF) process, in which continuous fiber strands are coated with a thermoplastic curing agent, extruded with printing nozzles, and then stacked on the Onyx matrix. The force of the CFF is derived from the continuity of the fiber strands, and unlike the chopped fiber, it absorbs and distributes the load over its entire length. According to the values provided by the manufacturer, carbon fiber is six times stronger than Onyx and eight times harder [23].

The CFRP 3D printing process consists of two steps per layer. First, a thermoplastic resin is extruded to form the filler and shell of a part and is used as the matrix material of a composite. Next, the continuous carbon fiber is ironed into a matrix to form a backbone of 3D-printed parts, whereas the thermoplastic matrix acts as the skin. Forming a backbone in a particular pattern enables the implementation of localized fiber placement optimized according to the way the part experiences the load, to provide strength accurately to the required area.

4.2. Design of ultrasonic fatigue test specimen

In aerospace and automatic applications, engineers and research scientists inevitably need to consider the feature loading and life of CFRP. However, unlike a metallic material, the microstructure of CFRP has anisotropy and heterogeneity, and therefore, the fatigue behavior is extremely complicated to characterize. Additionally, it is necessary to analyze the effects of various parameters (ply configuration, stress ratio, laminate thickness, fabric type, loading condition, and fiber content) on the feature properties of the composite structure [24].

Particularly, the fiber orientation requires intensive analysis because the aspect of the load that can endure changes depends on the direction in which the part is loaded. Therefore, this study evaluated the fatigue characteristics that change to structural anisotropy and heterogeneity, implemented according to the fiber orientation of the composite with specimens of three stacked orientation angles.

The specimen was composed of 20 layers, as shown in Figure 1; one is stacked with four layers on the base fiber orientation so that the
maximum CFF is stacked; the remaining space filled with Onyx is stacked with 12 layers. Finally, four layers of onyx were stacked on the top to finish the surface. As shown in Figure 1, specimens were fabricated in the 0° and 90° directions by stacking a unidirectional carbon fiber (UD) pattern in which all 20 layers were stacked in the same direction, and a bidirectional carbon fiber (BD) pattern was stacked in the vertical direction (90°).

Traditional fatigue tests, such as mechanical or hydraulic tests, test the fatigue life by transferring external forces from the test apparatus to the specimen at a frequency different from the natural frequency. However, the fatigue life tested with ultrasound must have an external frequency transmitted to the specimen at the natural frequency of the mode shape with a longitudinal vibration displacement. Therefore, the dynamic elastic modulus was measured, and the specimen was designed based on the elastic wave theory [25].

The dynamic elastic modulus measurement for the specimen shown in Figure 2, was performed according to the sonic resistance method of ASTM E1875 [26]. To measure the vibration displacement in free motion, a bar-shaped CFRP specimen (90 (l) × 16 (w) × 3.5 (h) mm) was supported with a thread. A small and light piezoelectric element (PZT, Physik Instrumente (PI) GmbH & Co., KG, Karlsruhe, Germany) was attached to one end and the other end was attached to a LDV (OFV-352, Polytec GmbH, Waldbronn, Germany). The frequency was swept using a digital signal analyzer (DSA, HP-35670A, Agilent Technologies, Inc. Santa Clara, CA, USA). The natural frequency of the longitudinal vibration mode was derived using a fast Fourier transform (FFT) based on the measurement displacement. The specimen design process was from the previous published paper [27]. The physical properties measured are listed in Table 1.

Figure 3 shows a schematic of the fatigue test specimen; the design variables according to the fiber orientation are listed in Table 2.

| Table 1. Physical properties of CFRP according to fiber orientation. |
|---------------------------------------------------------------|
| Property | UD 0° | UD 90° | BD |
| Density (g/cm³) | 1.234 | 1.207 | 1.207 |
| Natural frequency (kHz) | 25.6 | 21.4 | 10.1 |
| Dynamic Young’s modulus (GPa) | 23.3674 | 15.9751 | 3.5584 |

4.3. FEM analysis for specimen design validation

The suitability of the design dimensions determined through the dynamic elasticity measurement and theory was validated through an analysis model configured using FEM to calculate the vibration frequency. The analysis was performed using ANSYS software; the vibration phenomenon was verified using modal and harmonic analyses. For the FEM analysis, the specimen was constructed based on a shape calculated previously. The physical properties for the analysis were derived from tensile tests as presented in Table 3. For carbon fibers, a vertical anisotropic material was used to simulate the real phenomenon. The specimen shape was set according to the orientation angle to fit the design value of the specimen. After applying a mesh of approximately 0.1 mm to express the shape of the mode shape, the stacking condition was set. As previously set (in specimen printing), 20 layers were configured; the fiber angles were set according to the stacking pattern. The shape and grid were constructed according to the stacking conditions. The analysis model shown in Figure 4 was constructed. According
to the size of each specimen was connected to a conjugated horn as bonded contact, and the force was set to be well-transmitted.

In this study, we performed a one-axis tensile-compression fatigue test. A suitable mode shape was established through modal analysis and its frequency was confirmed. Figure 5 shows the analysis results of UD 0°; the resonance frequencies of each specimen mode were calculated as 20046 Hz (UD 0°), 20036 Hz (UD 90°), and 20034 Hz (BD). The results of this analysis confirmed that resonance occurred for the fatigue test device.

Following the modal analysis, a harmonic analysis was performed to analyze the amount of deformation and applied stress of the specimen. An excitation force was applied to the specimen end similar to the process used for the ultrasonic fatigue test. A harmonic response was confirmed at a frequency of 20 kHz. As shown in Figure 6, the tensile and compressive behavior of the specimen was confirmed; the stress was concentrated in the fracture in the center of the specimen.

5. Ultrasonic fatigue test

Conventional studies on ultrasonic fatigue test (28, 29, 30, 31) have primarily focused on isotropic ferrous or non-ferrous metal materials; the specimens were tested using a hourglass-type cylindrical or plate shape. Recently, with the increasing application of composite materials, research on the applicable test methods of polymers to evaluate high life is urgently required (in line with the trend of high efficiency and lightness). Therefore, in this study, 3D-printed specimens were fabricated using CFRP, a representative lightweight material, and a 20 kHz ultrasonic fatigue test device was used for the fatigue life evaluation as shown in Figure 7. The devices typically include the following [25]:

1. Power generator capable of converting a voltage signal of 60 Hz into a sine wave of 20 kHz
2. Piezo electric transducer that can convert electrical signals from power generators to longitudinal ultrasonic waves (mechanical vibration) of the same frequency
3. Ultrasonic horn to amplify the transducer’s vibration to the strain amplitude transmitted to the center of the specimen

The test principle of the resonance of the specimen enables ultrasonic fatigue testing as shown in Figure 7. Depending on the power set (%), the signal generated by the generator vibrates the PZT, which is transmitted to the horn. The amplified vibration signal is transmitted to the specimen. A tensile and compression deformation occurs at the center and the fatigue test is performed. The displacement was measured using an optical fiber sensor at the free end of the specimen, and the stress at the center of the specimen was calculated. If the experiment is carried out continuously, a gigacycle (109 cycle) can be reached within 14 h.

The specimen was fabricated by processing the M6 tap at the end of the horn to obtain a firmly fixed and stable resonant contact force. However, when the experiment was conducted under continuous conditions, the cyclic load was transferred to the specimen at a high speed, and heat was generated inside the specimen owing to friction by strain. Cooling is essential because the Onyx matrix has a low heat definition temperature of 145 °C and carbon fiber reinforcement of 105 °C. Therefore, the on and off times of the fatigue tester were set to 0.3 s and 10 s to cool the specimen during the rest time. As shown in Figure 7, two cooling nozzles were configured to spray cooling air into an angle that cooled the frictional heat on the surface contacting the horn with the specimen and the internal frictional heat at the center of the specimen.

The specimen was processed based on the configured design. The results were verified through FEM, and the number of fiber layers configured is listed in Table 4. The carbon fiber arrangement of each specimen is shown in Figure 8. The BD specimen was set so that the carbon fiber of the 12 layers were evenly distributed by repeating four layers for each angle three times.

6. Results

For the fatigue test, 3D Printing CFRP specimens were fabricated. The shape of the specimen, arrangement of the carbon fiber, and screw for coupling with the fatigue tester, are shown in Figure 9(a, b, c). The surface is covered with Onyx as described above. Owing to the characteristics of the FDM method, the path passed by the nozzle was visible on the specimen surface and was slightly rough, but the dimension error of the specimen was negligible, and the resonance at 20 kHz was maintained smoothly.

6.1. Fatigue life

The life measured in each experiment is shown in Figure 10. It can be observed from the graph that there is a significant difference for each orientation angle of the CFRP fibers. In the case of the UD 0° and BD specimens, the slope was different based on the lives of approximately 5373 and 3125 times, and this trend appears to be a characteristic of the composite material. The trend of the fatigue life was measured under stress below a certain level, and under high-stress conditions; the life of the 0° specimen was measured to be longer. Under high stress, the life varies depending on the amount of the 0° carbon fiber; however, it was determined that there was no significant difference because the stress distribution between the matrix and reinforcement was smooth at a certain level.

Because of the internal structure of the specimen, the fatigue durability of the UD 90° specimen where the carbon fiber was not subjected to stress, was very low; there was no difference in the slope of the life curve observed in the other specimens.

### Table 3. Material properties measured through tensile test.

| Property                  | Onyx (matrix) | Carbon fiber (reinforcement) |
|---------------------------|---------------|------------------------------|
| Tensile modulus (MPa)     | 1400 X        | 37403 XY                     |
| Shear modulus (MPa)       | 518.52 XY Z   | 14386 XY Z                   |
| Poisson ratio             | 0.35 XY YZ ZX | 0.35 0.3 0.25                |

![Figure 4. FEM model of Modal harmonic analysis.](image-url)
Based on the fracture surface of the specimen, it was confirmed that the fracture of each specimen was because of the destruction of the onyx used as a base material and not by the destruction of the carbon fiber. In the 0° specimen of Figure 11(a), it is observed that the crack started from the part where the fiber of the bent part ends, and the crack progressed along the fiber. Figure 11(b) shows that cracks started at the curved portion of the 90° specimen, and occurred in the direction of the fiber in the direction of 90°. The BD specimen in Figure 11(c) shows that the cracks were generated and bent at a right angle. As the fibers were crossed and arranged, it was confirmed that the base material was destroyed by the cracks.

6.2. Fracture analysis

6.2.1. Evaluation of equivalent material property

Unlike materials with a single property, it is difficult to interpret the fatigue life of a composite material. This is because there is a mixture of materials with different rigidities and life expectancies in one part, and the criteria for the stress imbalance and destruction are ambiguous. In this analysis, the fatigue life was numerically analyzed by applying equivalent physical properties to the material. Therefore, a practically applicable analysis model was constructed to solve this problem.

To derive equivalent physical properties, a unit grid was constructed using an ACP module; the physical properties were derived by appropriate analysis. In this study, orthotropic elasticity was applied to a fatigue analysis specimen to consider the characteristics of CFRP. Owing to the nature of 3D CFRP materials, the tensile characteristics vary significantly by direction and an actual analysis model can be constructed.

A specimen with an area of 2 × 2 mm was constructed as the size of the unit lattice. The lamination pattern consisted of a unidirectional carbon fiber (UD) and bidirectional carbon fiber (BD) pattern to represent the fatigue test specimen. The entire height was 2 mm; tensile

| Table 4. Orientation of carbon fiber layer. |
|------------------------------------------|
| **Unidirectional Carbon fiber (UD)**     | **Bidirectional Carbon fiber (BD)** |
| [0°] × 12 Layer                          | [90°] × 12 Layer                   |
| [0°] 90° 90° 0°] × 3 Layer               | [

Figure 5. Modal analysis of UD 0° specimen.

Figure 6. Harmonic response result of specimen.

Figure 7. Ultrasonic fatigue tester and resonance method [32].
analysis was performed for each direction to determine the anisotropic properties. Figure 12(a, b, c, d) shows the results of the tensile analysis, and the derived tensile properties are listed in Table 5.

As shown in the results, it is observed that the elastic modulus varies depending on the difference in the laminated pattern of fibers. In the case of the BD pattern, it was confirmed that the Y-axis rigidity was significantly increased compared to the UD pattern, and the X-axis rigidity was partially decreased. In the case of UD, the shear stress was also strong in the pre-stage number only in the YZ plane; however, in the case of BD, the shear coefficients in the YZ and ZX planes increased. This difference is probably because the concentration of stress inside the material is transferred differently from the onyx and carbon fibers depending on the fiber arrangement. The analysis results show that the Onyx layer does not receive considerable internal stress; the internal fiber layer covers most of the stress. Based on these results, it was determined that the arrangement of the carbon fiber in the direction that receives the major load could be changed to optimize the specific rigidity.

6.2.2. Evaluation of fatigue life curve through FEM

Fatigue analysis was performed based on the derived physical properties and the results were measured using an ultrasonic fatigue test. A tensile analysis was performed by assigning an equivalent mechanical property to the part depending on the shape of the fatigue test specimen (Figure 13). The UD 90°/C14 specimen was set by rotating the UD property 90°/C14 based on the Z-axis and setting it to be tensile based on the Y. Additionally, a specimen (BD_C) with a change in the arrangement of the carbon fibers was prepared. The difference in life results according to the difference in the in-pattern difference was compared. This specimen was similar to the BD condition, but a concentric pattern in which carbon fiber was placed along the rim was added to relieve and disperse stress as shown in Figure 13 (BD_C). The UD condition was set based on cylindrical coordination in the curved part of the specimen, and the BD condition capable of stress dispersion was set inside.

The tensile test was performed based on the physical properties. For the fatigue analysis, structural analysis, which is the basis for calculating fatigue life, is required. The stress applied to each element of the specimen is calculated through structural analysis. The expected life is
determined by substituting the obtained value into a fatigue life curve. Tensile analysis was performed by setting the fixed surface and force surface to boundary conditions at both ends of the specimen. Figure 14 shows the different aspects of the stress change that occurred based on the physical properties of the specimen. The young's modulus value of the specimen was computed as low because onyx primarily deals with stress. For the BD_C material, it was confirmed that as the concentration pattern of the outer layer was added, the carbon fiber covered the main stress, and the stress distribution in the central part was more evenly generated than in the other samples. The fatigue life was derived based on the results of the tensile analysis and compared by applying a tensile load of 120–1400 N based on the physical properties of the specimen. The external force application conditions of the fatigue analysis were analyzed and compared based on the stress ratio $R = C_0 / C_1$ as in the ultrasonic fatigue test. The mean stress effect was ignored because it was based on $R = -1$. The criteria for destruction in the ultrasonic fatigue tests are when specimen no longer resonates. Experience shows that 40–60% destruction occurs because the life expectancy in FEM is applied according to the stress assigned to each element. The scale was partially adjusted to correct the difference in criteria. Figure 15 shows a comparison between the analytically derived fatigue test and life expectancy derived from the actual test. Although differences occurred under high stress conditions, the life curve was similar to the actual experiment. It was confirmed through the UD specimen results that the life changed according to the carbon fiber angle. From this analysis, it was concluded that the life confirmed through the ultrasonic fatigue test could be derived accurately through numerical analysis. The lifespan was derived interpretively for the specimen with concentric conditions applied to the rim of the specimen. The expected life of the BD_C specimen shows that it was approximately 7 MPa stronger than that of the BD specimen. As previously confirmed through the tensile analysis results, the fatigue life increased through stress dispersion. Consequently, it was confirmed that an interpretation procedure configured to determine the life of a component made of CFRP material, could determine the life according to the stacking configuration or stacking direction. Additionally, it was confirmed that the differences and increases in life could be determined. The comparison results from the analysis show that the stress was dispersed by the carbon fiber surrounding the outer edge of the specimen; this stress was evenly distributed in the interior arranged in the BD direction. Based on this interpretation, carbon fiber may be disposed of

| Value                  | UD  | BD  |
|------------------------|-----|-----|
| Elastic modulus (GPa)  | X   | 28.899 | 28.62 |
|                        | Y   | 3.3191 | 28.511 |
|                        | Z   | 3.3221 | 3.3237 |
| Poisson ratio          | YZ  | 0.3   | 0.3   |
|                        | ZX  | 0.35  | 0.35  |
|                        | XY  | 0.35  | 0.35  |
| Shear Modulus (MPa)    | YZ  | 726.67 | 675.67 |
|                        | ZX  | 368.32 | 606.68 |
|                        | XY  | 366.62 | 382.97 |

Table 5. Calculated elastic and shear modulus of material property.
Figure 13. Fatigue simulation part; The physical properties were applied according to the coordinate system shown in the figure. The curved edge of the BD_C applied the rotation coordinate system to input the physical properties so that the physical properties were input according to the curvature.

Figure 14. Tensile test result for fatigue life calculation.
on the edge of a component manufactured with CFRP 3D printing or a part where stress may be concentrated to relieve and disperse stress, and it may cause a significant life increase. The arrangement of the carbon fiber in the local area is difficult to apply in the existing commercialized CFRP prepreg molding process, but it appears that the strength and durability can be effectively increased when used in combination with 3D printing.

7. Conclusion

In this study, an ultrasonic fatigue test specimen was manufactured using CFRP 3D printing to derive the fatigue life of the material. Particularly, UD and BD specimens were designed in accordance with the direction of the carbon fiber contained in the reinforcing material in the specimen. The resonance frequencies according to each processing condition were measured and specimens were designed accordingly. Modal and harmonic analyses were conducted using FEM to verify the designed value. The resonance at 20 kHz was confirmed by numerical analysis. The designed specimen was extensively analyzed from low to high cycles through an ultrasonic fatigue test, and the differences in the life of each specimen were compared and confirmed.

Additionally, the fatigue failure phenomenon was simulated using FEM based on the life analysis results of the specimen. For practical prediction, the shape of the unit size was modelled according to the stacking pattern of the specimen, and the physical properties were derived through numerical analysis. The derived physical properties are orthogonal anisotropic properties, and fatigue life analysis is performed by applying the physical properties secured through ultrasonic fatigue tests. It was confirmed that the analysis results for each lamination condition were consistent.

In the case of the CFRP 3D printing used in this study, a detailed arrangement of the CFRP according to each location and shape is possible. In other words, the specific strength can be efficiently secured by arranging the CFRP according to the direction of the force received by the part. To confirm this effect, a design was proposed to improve the fatigue life and durability by arranging a carbon fiber along the outer edge of the specimen shape. The life increase was determined analytically.

Based on these results, it is considered that there is sufficient merit in our study compared to the existing CFRP processing methods. Although there may be problems in terms of the homogeneity and completeness of the material, such as internal pores, owing to the FDM method, its weaknesses could be overcome by the degree of shape freedom and detailed arrangement of the reinforcing materials. The processing method was comparable to the existing methods.

This research could optimize the volume fraction of carbon fiber according to an external load, and in the same volume situation, it would be possible to print a material with improved strength and durability without changing its shape and volume by adjusting the stacking angle of CF to the external load. In a future study, we will propose to compare the difference in stress according to the CFRP volume fraction of the specimen, and in particular, investigate the difference in durability according to the anisotropy of the material.

Declarations

Author contribution statement

Chang-ho Jung: Performed the experiments and numerical simulation; Analyzed and interpreted the data; Wrote the paper.
Youngae Kang: Performed the experiments; Fabricated the specimens; Analyzed and interpreted the data; Wrote the paper.
Hyunseok Song: Performed the numerical simulation; Analyzed and interpreted the data; Wrote the paper.
Moon Gu Lee: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.
Yongho Jeon: Conceived and designed the experiments; Fabricated the specimens; Analyzed and interpreted the data; Wrote the paper.

Funding statement

Prof. Yongho Jeon was supported by Ministry of Trade, Industry and Energy [20206410100080].
Hyunseok Song was supported by Ministry of Science and ICT, South Korea [2019-0-00148].

Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interest’s statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20206410100080) and by Institute of Information & communications Technology Planning & Evaluation (IITP) grant funded by the Korea government (MSIT) (No. 2019-0-00148, Development of Dual Convergence Security Technology on Touch Control System using Smartphone for the control of Autonomous Driving Vehicle). Authors would like to thank Editage (www.editage.co.kr) for English language editing.

References

[1] J. Belter, A. Dollar, Strengthening of 3D printed fused deposition manufactured parts using the fill compositing technique, PLoS One 10 (2015), e0122915.
[2] T. Ngo, A. Kashani, G. Imbalzano, K. Nguyen, D. Hui, Additive manufacturing (3D printing): a review of materials, methods, applications and challenges, Compos. B Eng. 143 (2018) 172–196.
[3] O. Mohamed, S. Masood, J. Bhowmik, Optimization of fused deposition modeling process parameters: a review of current research and future prospects, Adv. Manuf. 3 (2015) 42–53.
[4] A. Sood, R. O’dar, S. Mahapatra, Parametric appraisal of mechanical property of fused deposition modelling processed parts, Mat. A mp; Design 31 (2010) 287–295.
[5] P. Alam, D. Mamalis, C. Robert, C. Floreani, C. O Badeaigh, The fatigue of carbon fibre reinforced plastics - a review, Compos. B Eng. 166 (2019) 555–578.
