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Development of a bendable pyramidal kagome structure and its structural characteristics

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ABSTRACT

A sandwich construction is an effective lightweight structure. Conventionally, sandwich structures have been fabricated as plane panels with limitation of application to curved components. In this work, a bendable structure that can be applied to the curved surface was developed based on the pyramidal kagome (PK) structure. The bending zone adaptable to the curved surface was designed between the neighboring PK structures. The PK sandwich structure was strengthened by developing the cross-sectional design of the strut. The mechanical characteristics were investigated by three-point bending test and compression test. The semi-circular cross-section (SCC)-based PK sandwich structure showed improved bending stiffness and maximum bending load over those of the conventional flat rectangular cross-section (FRC)-based PK sandwich structure. The curved PK sandwich structure was applied to the curved component.

1. Introduction

Lightweight structures are attracting increasing attention in many fields. A sandwich structure composed of stiff faces and an inner core is one of the solutions to achieve the lightweight problem. Conventionally, a honeycomb sandwich structure has been applied to the structural purposes because of its high specific stiffness [1–3]. Research works regarding the fabrication and the application of truss-based sandwich structures have been conducted for an octahedral truss [4], pyramidal truss [5,6], tetrahedral truss [7,8], and kagome structure [9–11]. Among these structures, truss-based sandwich structures are more flexible than other types of sandwich structures from the viewpoint of adaption to curved surfaces [12]. Moreover, truss-based structures are easier to integrate with other functional properties, such as heat insulation material or soundproof material, by inserting the functional materials inside the open cell structure [13,14]. Optimization of the cross-sectional shape of the struts and the fabrication method were developed by recent research works to enhance the structural properties [15,16]. A tubular cross-section-based truss core and a circular-wire cross-sectional truss core are generally applied to the cross-section of the strut. However, fabrication processes of various cross-sectional strut shapes are subject to further investigation.

Most of the sandwich structures in these research works were fabricated in the flat panel form, and its range of application was very limited because the industrial components generally do not use the panel shape. Some research works were conducted for the fabrication of curved sandwich structure. A sheared dimple core was developed for the curved sandwich structure [17]. However, the bending deformation of the dimple core for the curve adaption might induce residual stress and defects during the bending process. Recently, an interlocking method for the curved sandwich structure was suggested [18]. However, the radius of curvature was limited and the sandwich structure could be bent in only one direction.

In this paper, the curved sandwich was developed based on the pyramidal kagome (PK) structure [19]. Bending zones for the bending deformation were designed between the neighboring PK structures. The cross-sectional shape of the strut of the PK structure was designed as semi-circular cross-section (SCC) and glass fiber reinforced plastic (GFRP) face sheets of thickness of 0.6 mm were applied as face sheets. The mechanical properties were investigated by the three-point bending test and compression test, and the results were compared with the flat rectangular cross-section (FRC)-based PK sandwich structure. The curved sandwich structure was fabricated with SCC-PK structure and the curved GFRP face sheet.

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2. Development of the curved sandwich structure

2.1. Concept of the curved sandwich structure

Generally, most of the sandwich structures are fabricated as a plane panel even though many industrial components are of curved shape. There were some previous attempts to fabricate a deformable sandwich structure. In these research works, the sandwich panel was bent into the curved target shape and the critical bending radius was defined as the minimum radius until the specimen failed. However, the bent sandwich structure was not stable because of its residual stress and the structure could be fractured with small external loads. In this research, the sandwich structure was designed to be bent without residual stress by applying a bending zone as shown in Fig. 1.

The bending zone was designed in the gap between the neighboring PK structures. The gap is desirable from the view point of stable bending and material saving. The gap distance was determined to be bent via a stable shear mode according to the bending deformation window [21]. When the gap distance between the PK structures was too close, the sandwich structure was bent via the local compression at the center. In this case, the failure mode was not stable because of buckling. From the result, the gap distance between PK structures was determined to be 3.8 mm which allowed the PK sandwich structure to bend in stable shear mode. The bending zone consists of upper and lower curved parts. These two curved parts in the bending zone of the inner core allowed tensile and compressive deformation when a PK inner core structure was bent into a curved shape and bonded with the face sheets. The bendable PK structure could be adapted to the curved surface without damage or unnecessary plastic deformation.

2.2. Cross-sectional design of the core strut

In the previous research works, the PK structure that had a FRC shape (FRC-PK) structure was developed [19]. The PK structure was strengthened by changing the cross-sectional shape of the strut. The geometrical moment of inertia was improved by changing the cross-sectional shape of the strut. The critical buckling load of the PK structure was improved as the moment of inertia increased because the critical buckling load is proportional to the geometrical moment of inertia of the strut. A tubular cross-section (TC) and a SCC were proposed in this work as alternatives to the conventional FRC-PK structure. The design and the dimensions of each cross-sectional shape are shown in Fig. 2. Although the cross-sectional areas were all the same as 0.6 mm^2, the geometrical moment of inertia of the SCC was 4.4 times as large as that of the FRC. PK inner core structures based on three cross-sectional shapes were designed for the analysis as shown in Fig. 3. The strut angle, θ, was 45° which was formed to be the optimum angle obtained from the previous research [19]. The height of the core, c, and the thickness of the core, t_c, were 3.6 mm and 0.4 mm, respectively. The widths of FRC, TC, and the SCC-PK structure, w, were 5.1 mm, 4.9 mm, and 5.5, respectively.

3. Analysis and design of the cross-section for the PK sandwich structure

3.1. Conditions for compression, shear, and bending analyses

The mechanical properties of PK sandwich structures with various cross-sections were investigated by the finite element method (FEM) by using commercial software (ABAQUS, Dassault systems, France). The material properties of polypropylene (PP) for the core material and GFRP for the face sheets were obtained by material tests and were employed for the analysis. Young's modulus, Poisson's ratio, and yield strength of PP were 1222 MPa, 0.35, and 15 MPa, respectively. Young's modulus and Poisson's ratio of the GFRP material were 30 GPa and 0.34, respectively. Four unit PK structures (2×2) were used in the compression and shear analyses and eight unit PK structures (8×1) were used in the bending analysis. The number of elements in the simulation for each FRC, TC, and SCC-PK structure was 12,160, 20,768, and 18,672, respectively.

The compression analysis was conducted with 1 mm of compression displacement from the upper side of the PK sandwich structure while the lower side of the PK was fixed. For the shear analysis, the shear displacement was assigned on the upper side with 1 mm of shear displacement, while the lower side was fixed. The bending model is shown in Fig. 4. The bending deflection was set to be 7.5 mm. The diameters of the rolls were 4 mm and the span length between the bottom supporting rolls was 75 mm. The bending specimen was modeled as a half model with a symmetric boundary condition.

The gap distance, s, between two PK inner core units was slightly different for each of the three cross-sections because of their different widths. The gap distance of each FRC, TC, and SCC-PK inner core unit was 2.0 mm, 2.9 mm, and 2.5 mm, respectively. The thickness

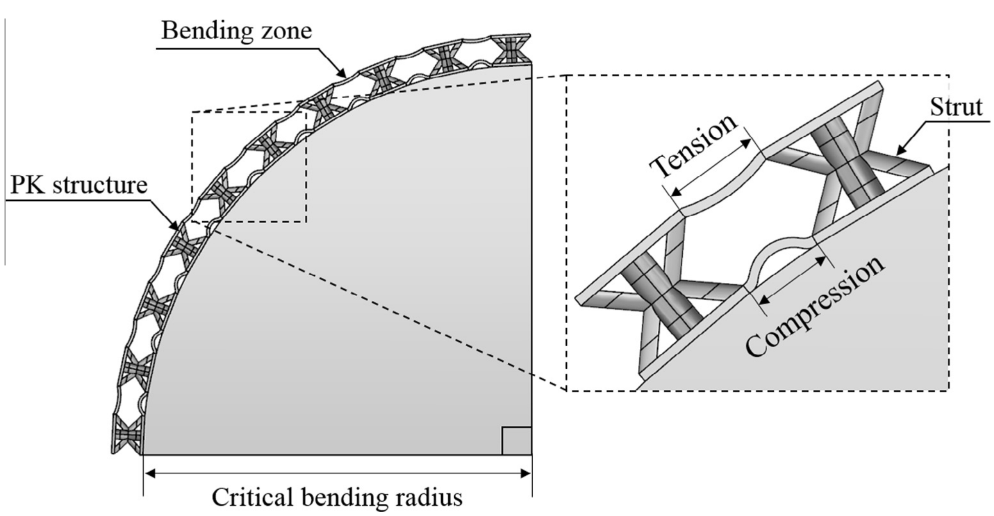


Fig. 1. Application of curved PK inner core structure to a curved surface.

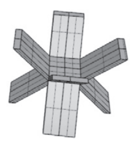
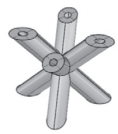
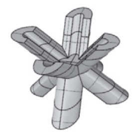
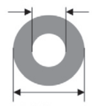
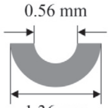
	Flat rectangular cross-section (FRC)	Tubular cross-section (TC)	Semi-circular cross-section (SCC)
Core design			
Cross-sectional shape	 0.4 mm, 1.5 mm	 0.34 mm, 0.94 mm	 0.56 mm, 1.36 mm
Cross-sectional area	0.6 mm^2	0.6 mm^2	0.6 mm^2
Geometrical moment of inertia	0.008 mm^4	0.037 mm^4	0.035 mm^4

Fig. 2. Geometrical moment of inertia with respect to the different cross-sectional shapes.

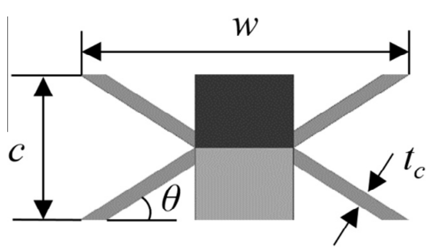


Fig. 3. PK inner core structure and the shape parameters.

of each of the face sheets was 0.6 mm and the width of sandwich structure was 4.2 mm. In the actual fabrication, the connecting part was necessary for the injection molding process of the PK structure as shown in Fig. 5(b).

3.2. Structural characteristics with respect to the cross-section of the PK structure

The effects of the cross-section of the PK structure on the mechanical properties of the PK sandwich structure were investigated by the FEM. The results for compression, shear, and bending analysis are shown in Fig. 5. In the compression analysis, the FRC strut buckled at low load and the struts could not sustain the compression load. On the contrary, buckling did not occur in the TC-PK sandwich structure or in the SCC-PK sandwich structure. The TC-PK sandwich structure and the SCC-PK sandwich structure sustained 3 times the compression load than the FRC-PK sandwich structure. The maximum compression load of the TC-PK sandwich structure was 3.8 times the maximum compression load of the FRC-PK sandwich structure. The compression stiffness of the TC-PK sandwich structure was 2.7 times that of the FRC-PK sandwich structure.

The load–displacement curves of shear analysis are shown in Fig. 5(b). The specific shear stiffness of the FRC-PK sandwich structure was 7.9 MN/kg·m and the shear stiffness of the SCC and the TC-PK sandwich structures was the same, 15.3 MN/kg·m. As mentioned above, the shear stiffness was increased by changing the cross-section of the PK structure from the FRC to the TC or the SCC. The maximum shear load was also increased by more than 2 times compared with the FRC-PK sandwich structure. When modeling the TC and SCC-PK structures, the empty center area among the contact points of the eight struts was filled to avoid stress concentration.

The bending stiffness of the TC and SCC-PK sandwich structures was 2 times as large as that of the FRC-PK sandwich structure. When the specimens were bent, the compression resistance at the center is the most important factor for the PK-based sandwich structures. If buckling occurs easily at the center of the specimen, then the sandwich structure will deform locally without shear deformation of the PK structures which will lead to a reduction of the bending load and bending stiffness. If the center structures sustain compression loads without severe buckling of the struts, then the shear resistance of the structure becomes more important for the remaining structures. From the results, the bending tendency of the TC and SCC-PK sandwich structures was strongly influenced by the shear characteristics of the structures because the center PK structures did not buckle. However, the FRC-PK sandwich structure buckled severely during the bending deformation and its bending load–deflection curves were considered to be influenced by its compression characteristics.

Fig. 6 shows the deformation of the PK sandwich structure located in the center area of the specimen after 7.5 mm of bending deflection. The struts of the PK sandwich structure based on the FRC were completely buckled, as shown in Fig. 6(a), while the TC and SCC-PK sandwich structures were not buckled. The heights of the compressed PK sandwich structures were 1.96 mm, 3.47 mm, and 3.18 mm following FRC, TC, and SCC-PK sandwich structures when the original distance between two face sheets was 3.6 mm. The height of the FRC-PK sandwich structure was compressed by more than 45.5% in comparison with its original height, while the TC and SCC-PK sandwich structures were compressed 3.6% and 11.6%, respectively.

The most effective cross-section was considered to be the SCC shape accounting for the compression, shear, and bending analysis results because the SCC shape showed higher strength in shear deformation and also in bending deformation than the other two shapes. In addition, it is also easier to fabricate an open type SCC-PK structure than a closed type TC-PK structure.

4. Fabrication of the specimen and the experimental set up

4.1. Fabrication of the SSC-PK sandwich structure

In the previous research work, the PK inner core structure was fabricated in three steps: flat mesh fabrication, pyramidal shaping,

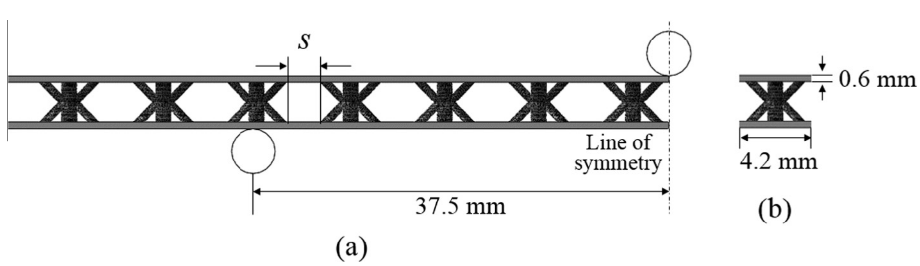


Fig. 4. Model of the three-point bending analysis: (a) front view, (b) side view.

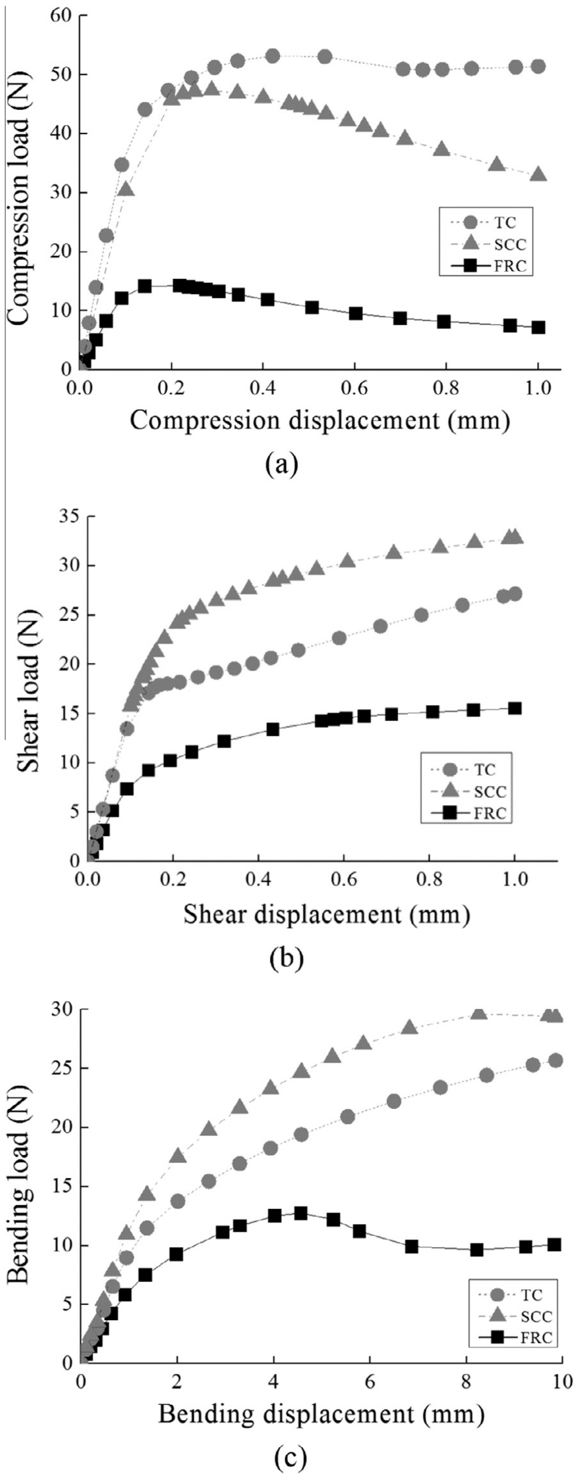


Fig. 5. FEM results: (a) compression, (b) shear, (c) bending.

and adhesive bonding process [19]. However, in this study, the three-step fabrication processes were simplified by one step of the injection molding process. The fabrication time was significantly reduced by removing two fabrication processes, and the defects due to adhesive bonding were removed.

The injection molding dies to fabricate the SCC-PK structure were developed as shown in Fig. 7. The injection molding process was conducted with the die temperature of 150 °C and a body force of 80 tons. The fabricated specimen is shown in Fig. 8. The SCC-PK inner core structure was fabricated as one line of a strip to form the SCC strut. The PP which has the melting index of 18 g/10 min was used as the material of the specimen. The dimensions of the specimen are presented in Table 1 and Fig. 9. The total length of the PK structure was 108 mm.

The SSC-PK sandwich structure and the FRC-PK sandwich structure were fabricated for the bending and compression experiments. The FRC-PK sandwich structure was fabricated by the following three steps: flat mesh fabrication, pyramidal forming, and adhesive bonding process [19]. The dimensions of FRC-PK structure are shown in Fig. 2. The width and the length of the specimen were not exactly same because the width of the SCC-PK structure and FRC-structure was different. Each unit width of SCC-PK structure and FRC-PK structure was 5.5 mm and 6.6 mm, respectively. Five SCC-PK structures and four FRC-PK structures were arranged for the three-point bending and compression tests. The total width of each FRC-PK sandwich structure and SCC-PK sandwich structure was 26.4 mm and 27.6 mm, respectively as shown in Fig. 10. The total numbers of FRC inner cores and SCC inner cores were 64 and 60, respectively. The specimen for compression was also fabricated to be similar in size as shown in Fig. 10(b) and (d). The total numbers of FRC inner cores and SCC inner cores for the compression test were 25 and 24, respectively.

GFRP faces were bonded to the constructed sandwich structures. The thickness of the GFRP face was 0.6 mm and the GFRP was plain weave glass fibers impregnated with epoxy resin. The face sheets were bonded by cyanoacrylate adhesive (AXIA 1500, AXIA, South Korea). Both the face sheet and the inner core were treated with primer (AXIA 1501, AXIA, South Korea), dried for 30 min and then the adhesive was applied and cured at room temperature for 24 h.

4.2. Experimental set up for the three-point bending test and the compression test

Three-point bending tests were conducted using a material testing machine (INSTRON 5583, Instron, USA). The radii of the upper and lower rolls were 4 mm. The span length was 75 mm as shown in Fig. 11. The cross-head speed was 2 mm/min.

The compression tests were conducted by using the material testing machine (INSTRON 5583, Instron, USA). Two cylinder shapes of polished stainless steel plates were used. The cross head speed was 0.5 mm/min. The mass of the FRC and SCC-PK sandwich structures for three-point bending test were 10.39×10^{-3} kg and 10.58×10^{-3} kg, respectively and the mass of the FRC and SCC-PK sandwich structures for the compression test were 4.22×10^{-3} kg and 4.29×10^{-3} kg, respectively.

4.3. Fabrication process for the curved sandwich structure

The minimum bending adaption radius was referred to as the critical bending radius (r_{cr}). The critical bending radius of the sandwich structure was expressed as the relative radius which was obtained by dividing the critical bending radius by the total height of the sandwich structure (h_t). Generally, the relative radius of woven metals are 130–160 [20]. The relative radius of the curved PK sandwich structure was calculated by considering the deformation of two bending zones shown in Fig. 1. The upper bending zone could be stretched as much as the difference value between the arc length of the bending zone and the gap distance. The arc length of the bending zone was 4.2 mm and the gap distance between the PK structures was 3.8 mm. Thus, the stretchable distance of the upper bending zone was 0.4 mm. If the lower bending strut was approximated to be compressed 0.4 mm, the critical bending radius was calculated as 54.7 mm. When the 0.6 mm thickness of face sheet

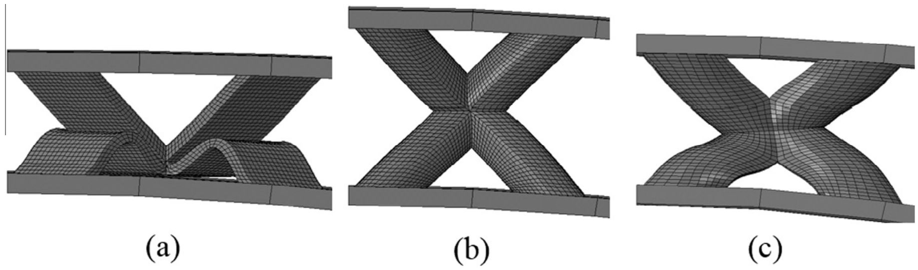


Fig. 6. Deformation of PK sandwich structure after 7.5 mm of bending deflection: (a) FRC, (b) TC, (c) SCC.

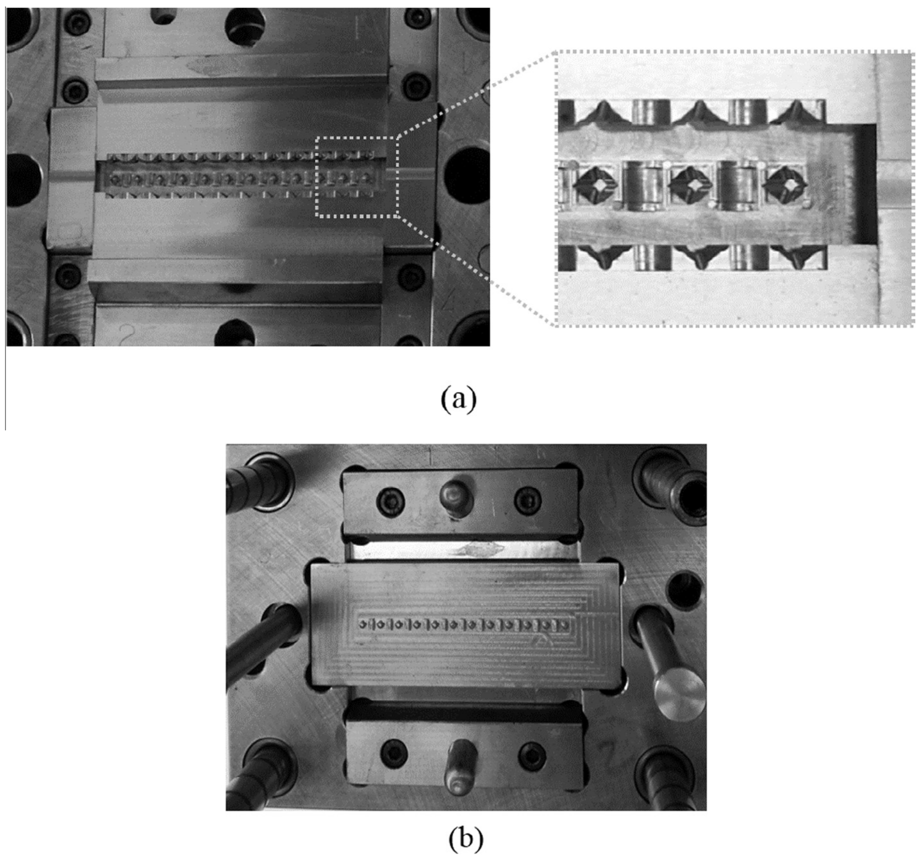


Fig. 7. Injection molding dies: (a) upper die, (b) lower die.

was applied, the relative radius of the curved PK sandwich structure (r_{cr}/h_t) was calculated as 10.5 which was just 8.1% of the conventional woven metals. This result indicated that the curved PK sandwich structure could be adapted to the various components with a small radius of curvature.

The PK sandwich structure is comprised of two curved face sheets and the bendable PK structure. The glass composite faces were fabricated using fabric type E-glass/epoxy prepreg (GEP118, SK Chemicals, South Korea) whose properties are listed in Table 2. Four plies of prepregs were stacked onto two curved molds which had the radii of 54.7 mm and 59.1 mm, and then cured using the autoclave vacuum bag degassing method according to the curing cycle shown in Fig. 12. The bendable SCC-PK sandwich structure was bonded to the curved GFRP face sheet by adhesive (AXIA 1500, AXIA, South Korea).

5. Results and discussion

5.1. Three-point bending test

The bending load–deflection curves of the SCC-PK sandwich structure and the FRC-PK sandwich structure are shown in Fig. 13. The maximum bending load of the SCC-PK sandwich structure was 37% higher than that of the FRC-PK sandwich structure. Moreover, the bending stiffness of the SCC-PK sandwich structure also increased 52% compared with the FRC-PK sandwich structure even though the gap distance between the neighboring PK structures increased more than 2 times. These results indicated that the PK sandwich structure could be used more efficiently by strengthening the cross-sectional shape of the strut in the viewpoint of material saving.

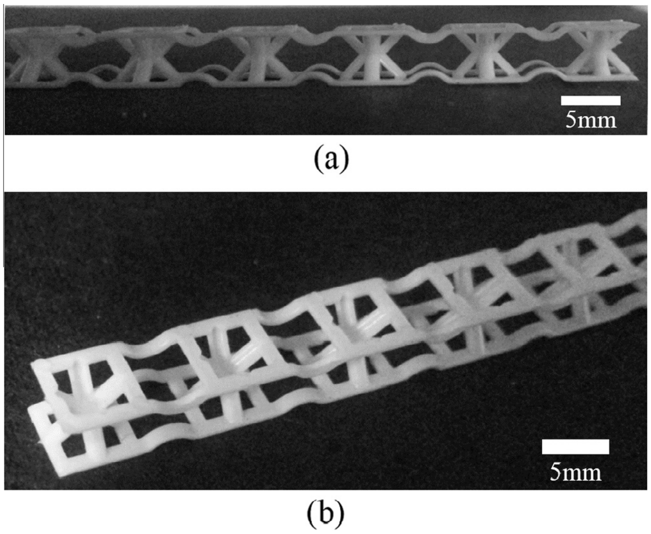


Fig. 8. Fabricated PK structure: (a) front view, (b) perspective view.

Table 1
Dimensions of the bendable PK structure.

Height of the PK structure, c (mm)	3.60
Height of the structure, h (mm)	4.40
Width of a unit PK structure, w (mm)	5.51
The strut angle, θ, (°)	45.0
Length of the bending zone, s (mm)	3.83
Inner radius of the bending zone, r_{ib} (mm)	1.74
Outer radius of the bending zone, r_{ob} (mm)	2.14
Inner radius of the cross-section of the PK strut, r_{ic} (mm)	0.28
Outer radius of the cross-section of the PK strut, r_{oc} (mm)	0.68

The bending deformations of both the SCC-PK sandwich structure and the FRC-PK sandwich structure are shown in Fig. 14. The SCC-PK sandwich structure was bent stably without the local compression failure as shown in Fig. 14(b) while the FRC-PK sandwich structure could not sustain the bending load and the cores at the center area were fully compressed because the moment of inertia of flat rectangular shape was very low.

5.2. Compression test result

The compression test results are shown in Fig. 15. The maximum compressive load of SCC-PK sandwich structure and FRC-PK sandwich structure were 760 N and 637 N, respectively. Considering the different PK numbers, a unit SCC-PK sandwich structure and a unit FRC-PK sandwich structure sustained 31.6 N and 25.5 N, respectively. The SCC-PK structures sustained the compressive load more efficiently because the width of unit core was smaller than that of the FRC-PK structure. Moreover, considering the unit width of the SCC-PK structure and the FRC-PK structure (which was 3.7 mm and 4.6 mm, respectively), five SCC-PK structures and four FRC-PK structures can be arranged in the same width. These results indicated that the SCC-PK sandwich structure and the FRC-PK sandwich structure sustained 158 N and 102 N of compressive load, respectively. The SCC-PK sandwich structure had 55% higher compressive strength than the FRC-PK sandwich structure in the same area.

The initial stiffness of both SCC and FRC-PK sandwich structure were similar. However, the stiffness of FRC-PK sandwich structure became low after 0.1 mm of compression displacement because the FRC easily buckled due to the low moment of inertia.

5.3. Fabrication of the curved sandwich structure

The PK sandwich structure was adapted to the curved surface as shown in Fig. 16(b). The radius of the lower face sheet was

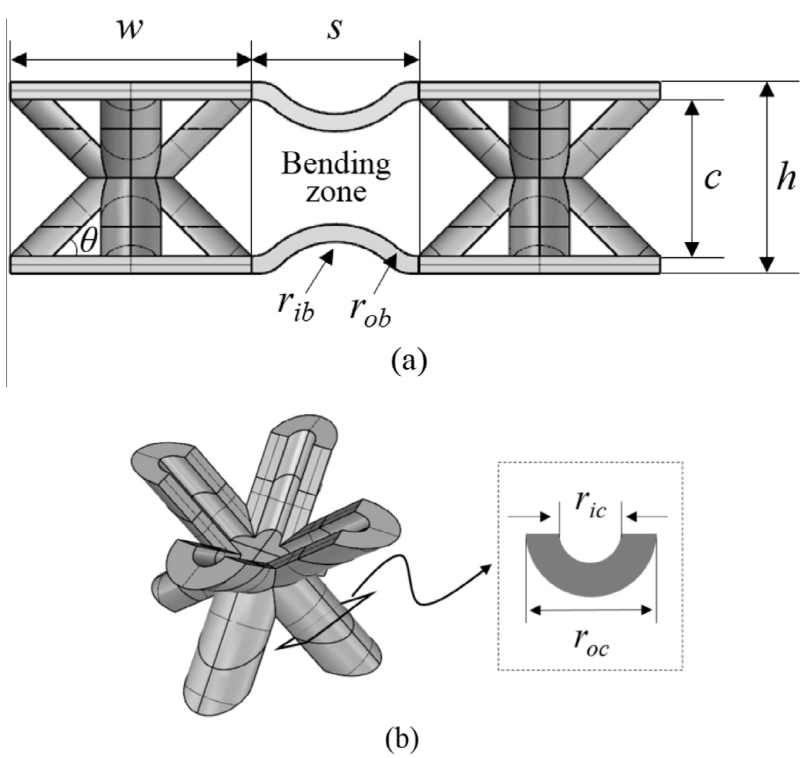


Fig. 9. Bendable PK structure: (a) front view, (b) perspective view.

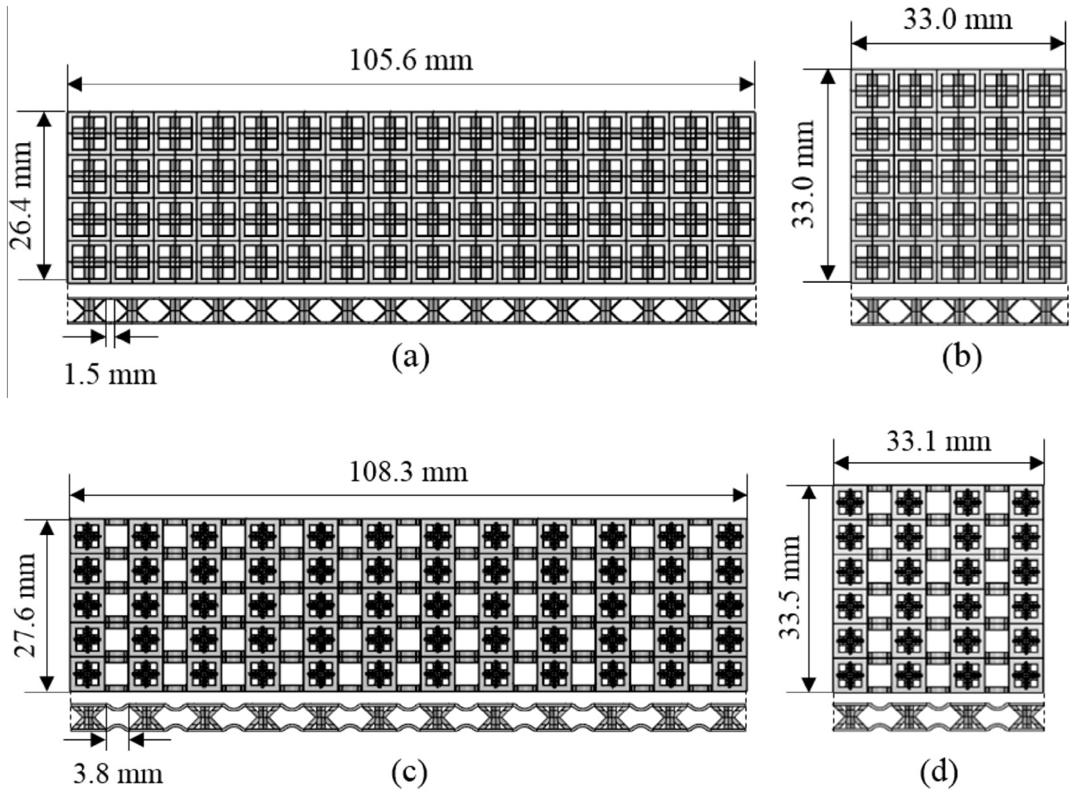


Fig. 10. Specimen configurations: (a) FRC-PK inner core for the three-point bending test, (b) FRC-PK inner core for the compression test, (c) SSC-PK inner core for the three-point bending test, (d) SSC-PK inner cores for the compression test.

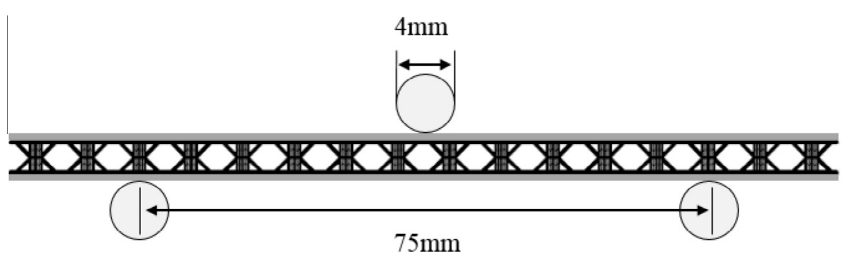


Fig. 11. Experimental set up for the three-point bending test.

Table 2
Properties of the glass fabric/epoxy composite.

In-plane modulus (GPa)	27.6
Areal weight (g/m^2)	267
Ply thickness (mm)	0.15

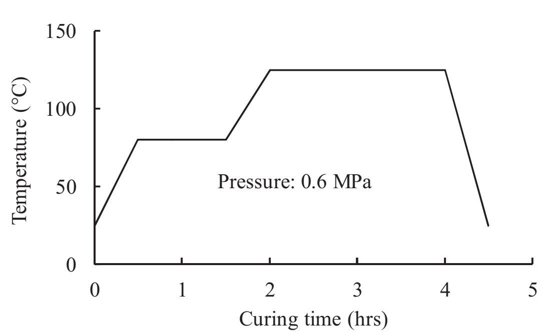


Fig. 12. Curing cycle for the fabrication of the glass composite face.

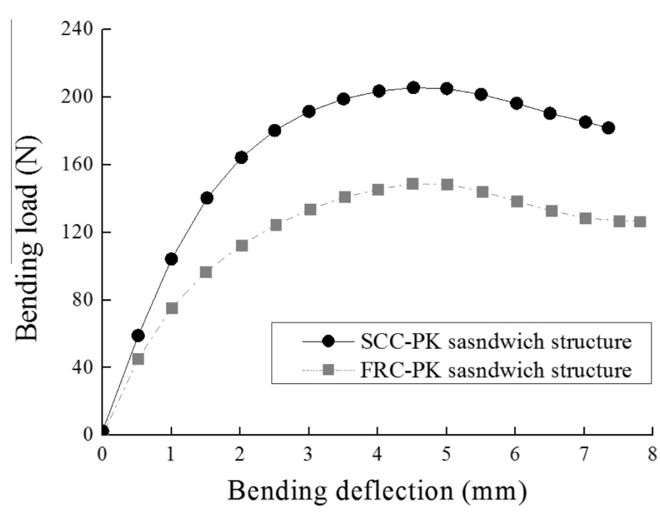


Fig. 13. Bending load–deflection curve according to the cross-sectional shape.

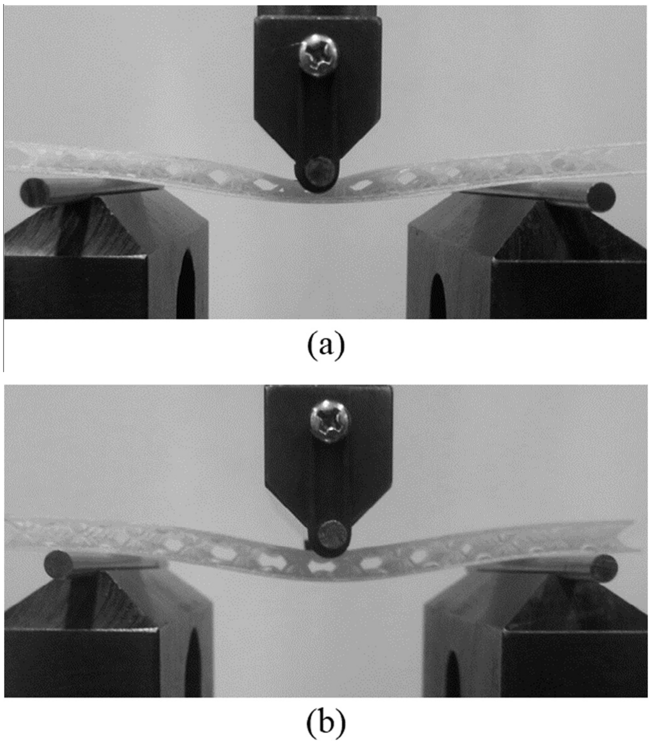


Fig. 14. Bending deformation of the PK sandwich structures: (a) FRC-PK sandwich structure, (b) SCC-PK sandwich structure.

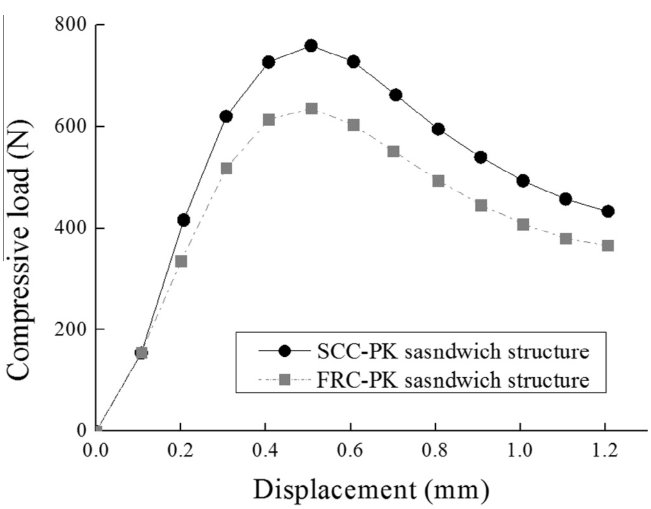


Fig. 15. Compressive load–displacement curve for different cross-sectional shapes.

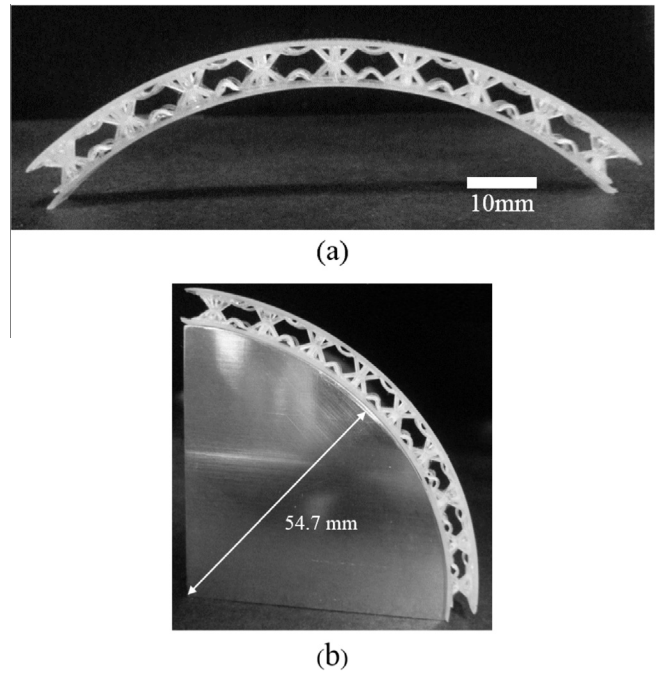


Fig. 16. Curved PK sandwich structure: (a) front view, (b) curved PK sandwich structure adapted to the curved surface.

54.7 mm and the radius of the upper face sheet was 59.1 mm. The PK sandwich structure was adapted to the curved face sheet without any failure and damage. Fabrication of the structure for realistic application and the investigation of the mechanical properties after curve adaption remain as topics of future work.

6. Conclusion

A pyramidal kagome structure (PK) was designed for the bendable sandwich structure and fabricated using the injection molding process. Moreover, the PK sandwich structure was strengthened by changing the cross-sectional shape from a flat rectangular (FRC) shape to a semi-circular shape (SCC). The geometrical moment of inertia of the SCC was 4.4 times greater than that of the FRC. The three-point bending and compression test were conducted and the results were compared with the flat rectangular cross-sectional (FRC) shape based PK sandwich structure. The maximum bending load and the bending stiffness of the SCC-PK sandwich structure increased 37% and 52%, respectively compared with the FRC-sandwich structure. The maximum compressive strength of the SCC-PK sandwich structure increased 55% compared to that of the FRC-PK sandwich structure.

The critical bending radius and the relative radius of the curved PK sandwich structure were 54.7 mm and 10.5, respectively. The relative radius was just 8.1% of the conventional woven metals which indicated that the developed structure could be adapted to the various components with a small radius of curvature.

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